Fixed Wireless Access 2019

Abstract: This report outlines the growing market for fixed wireless access equipment, including both licensed and unlicensed options. The scope ranges from sub-1 GHz to millimeter wave bands, including 802.11-based and 3GPP-based LTE and 5G radios. The five-year forecast illustrates the growth of the market for both infrastructure and terminals.

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MOBILE EXPERTS

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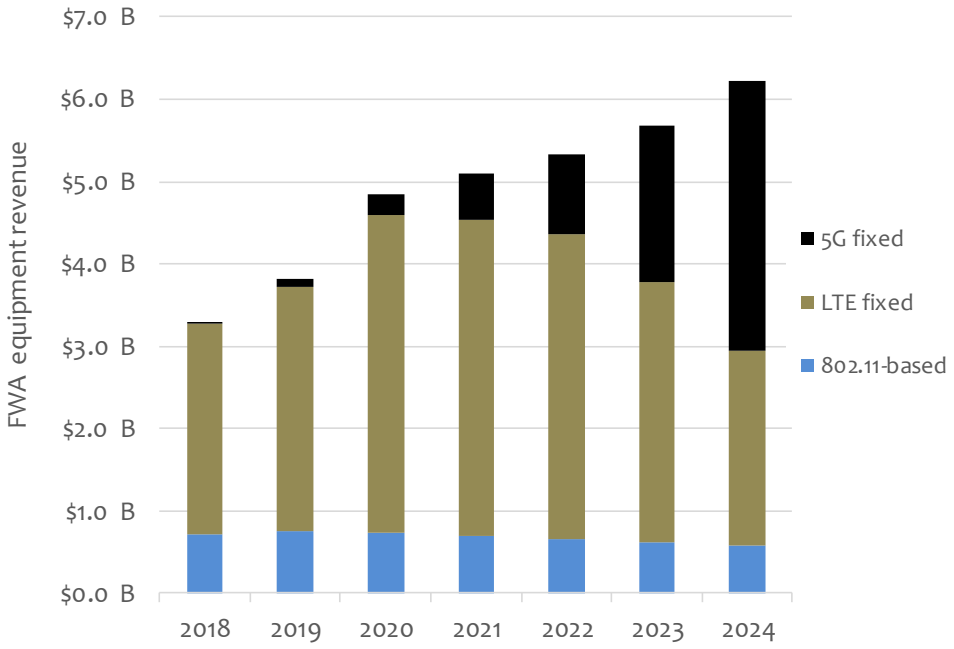
MEXP-FWA-19

1. EXECUTIVE SUMMARY

The fixed wireless access equipment market, excluding wireless backhaul, is expected to create over $30 billion of cumulative equipment revenue from base station access point (AP) and customer premise equipment (CPE) sales over the next six years from 2019 to 2024. CPE sales ($5.5 billion) are expected to represent the bulk of the total fixed wireless access equipment sales ($6.2 billion) in 2024. The remainder ($700 million) represents the annual sales of "dedicated" fixed wireless AP equipment (solely for the fixed broadband services)[1] in 2024. The overall fixed wireless access equipment market is expected to grow at 11% CAGR from $3.3 billion in 2018 to over $6.2 billion in 2024.



Source: Mobile Experts

Chart 1: Global Fixed Wireless Access Equipment Revenue, 2018-2024

While the 802.11-based fixed wireless access market remains flat during our forecast period, the combined 3GPP-based LTE and 5G fixed wireless segments are expected to grow quickly as major mobile operators increasingly look to share increased mobile broadband network capacity for both mobile and fixed broadband services.

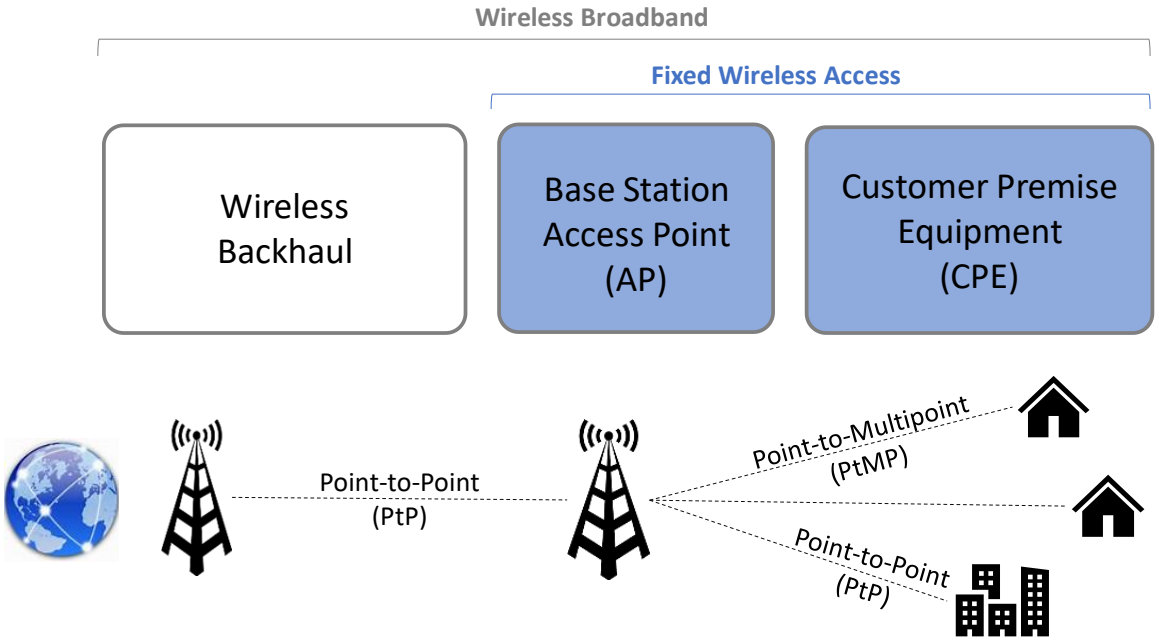
[1] Tier1 mobile operators are likely to share wireless infrastructure between fixed and mobile broadband services. Note that the primary base station RAN equipment sales going to Tier 1 mobile operators that are used for both mobile and fixed are not counted in our Fixed Wireless Access AP equipment sales.

The 5G fixed segment, in particular, is expected to grow quickly as operators worldwide look to leverage 5G fixed broadband for new revenue generation or simply as DSL replacements within their fixed broadband footprint. By 2024, the 5G fixed segment will represent over 50% of the total FWA equipment market.

The growth in the fixed wireless access is underpinned by strong demand drivers, including cord-cutting trends, additional spectrum bands coming online, and government subsidy programs worldwide. Moreover, the economic ROI of fixed wireless access continues to improve. Spectrum opportunities across licensed, shared, and unlicensed bands and technology advancements in 802.11ax and 5G, such as MU-MIMO and massive beamforming, enable higher throughput capacity and user speeds. Furthermore, the maturing ecosystems, including Wi-Fi 6, Terragraph, and 5G NR for fixed will bring economies of scale to broaden the respective 802.11-based and 5G fixed target markets.

2. FIXED WIRELESS ACCESS MARKET DEFINITION

In this market study, Mobile Experts is defining the Fixed Wireless Access (FWA) equipment market to denote base station access point (AP) and customer premise equipment (CPE) located on the subscriber's home or business location. The wireless backhaul equipment is excluded from our FWA equipment definition – though it is a significant part of the overall "Wireless Broadband" equipment market.



Source: Mobile Experts

Figure 1. Fixed Wireless Access (FWA) Market Definition

As depicted in the illustration of what's included in our FWA market definition, some portions of point-to-point radio equipment share are included in our FWA market definition if it is used for access. For example, a certain "high end" segment of the market--demanding hundreds of Mbps or even 1 Gbps service -- can only be handled using point-to-point systems today. In such cases, we include this aspect of point-to-point radio equipment in our AP and CPE equipment count.

3. MARKET ACTIVITIES

While fixed wireless has traditionally focused on underserved rural areas where economics of fixed broadband technologies didn't make sense, the evolving fixed wireless technologies and more importantly the availability of spectrum is opening up higher-tier market opportunities in urban and suburban areas – increasingly encroaching upon the traditional fixed broadband markets addressed through DSL, Cable, and FTTH.

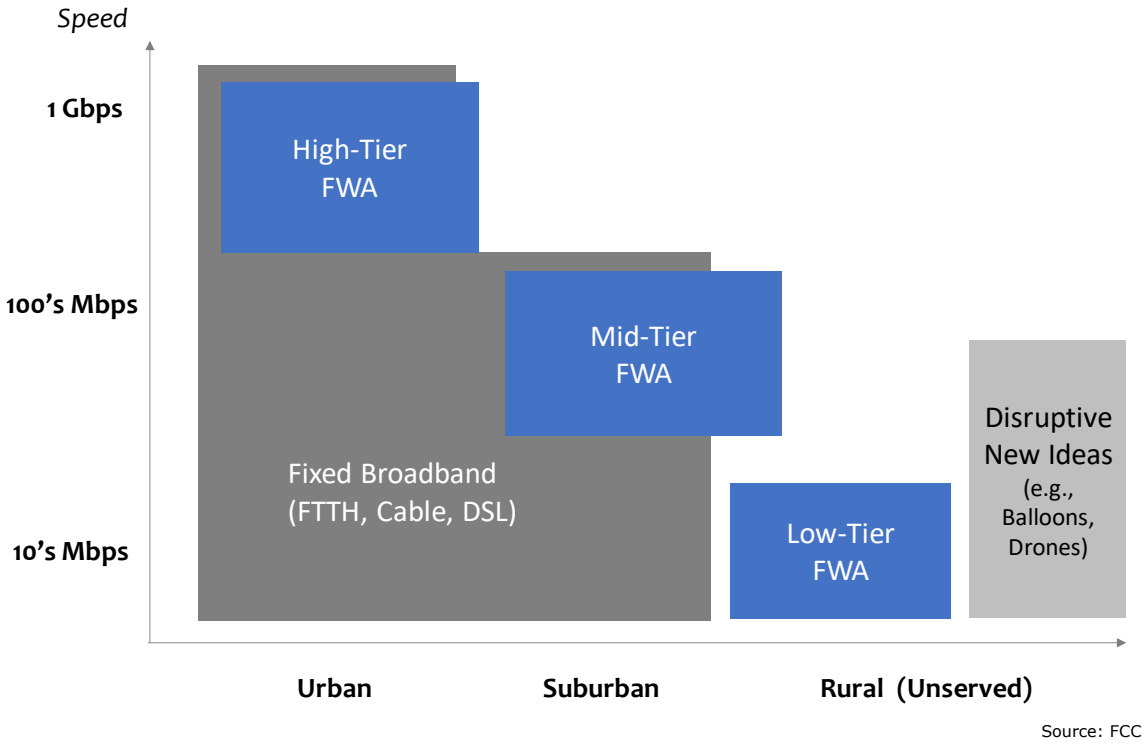


Figure 2. Evolving FWA technology can serve different market segments

The market activities in the fixed wireless access (FWA) have picked up a notch in the past year as one of the leading mobile operators touted FWA as one of the first use cases of 5G. The increasing market activities and pronouncements around FWA and opening of new spectrum bands in the mid 3.5 GHz and the millimeter wave bands have excited long-time wireless backhaul suppliers and new operators to explore FWA once again. Also, government programs like CAF II and Rural Digital Opportunity Fund in the USA and similar programs in other regions are adding fuel to the excitement around FWA.

Demand Drivers

Market demand for broadband services is unabated around the world. As more and more people come online for common "day to day" services from communications to commerce, the need to be connected is becoming ever greater. Meanwhile, there are still many homes that are unconnected to the Internet. Even for those who have broadband services to home, the need for higher speeds seems to outpace the ability to deliver. This accelerated pace of demand is exacerbated by the cord-cutting trend as well as entertainment alternatives from Netflix, Amazon, and other online streaming services become more prevalent through proliferating personal and home devices like Roku, smartphones, etc.

Connecting the Unconnected

According to the International Telecommunications Union (ITU), there are over 750 million homes and businesses around the world that are still unconnected as of 2017. While this is a great improvement from 850 million unconnected homes and businesses five years ago, there is still a big chasm – 44% of worldwide households and businesses are still unconnected. Asia has the most unconnected homes and businesses (~550 million). In the Americas, including North and South America, there are still over 100 million households and businesses without an Internet connection.

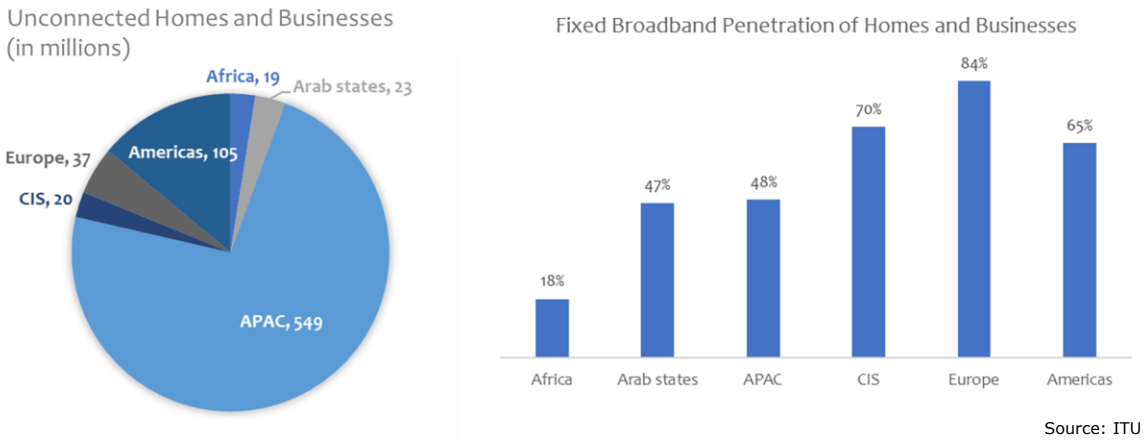


Figure 3. Fixed broadband penetration and Unconnected homes and businesses

The fixed broadband penetration varies by region as developed countries have more telecommunication infrastructure to deliver broadband services while many developing countries rely on the mobile connection for broadband services. Europe has the highest fixed broadband penetration at over 80% while Africa is still under 20% penetrated.

Need for Speed

Even in places with high broadband penetration, the broadband speed offer is sometimes not adequate to meet the demand. Some old telecommunication infrastructure based on copper is not capable of meeting gigabit service requirements. While fiber continues to be deployed, where it makes sense economically, it is not a panacea in all markets as the capital expenditure for wide-scale deployment is prohibitive in many markets. According to ITU, outside of APAC where fiber deployment was incentivized through government mandates and other actions, fiber comprises a relatively small portion (~15%) of overall fixed broadband subscriptions. The old copper-based DSL is still the dominant means by which fixed broadband service is delivered in most places. While new technologies such as G.fast and others continue to make advancement, copper-based broadband services are likely to fade in most markets as the physical medium of copper is not conducive for handling very high throughput network services due to interference and cross-talk issues.

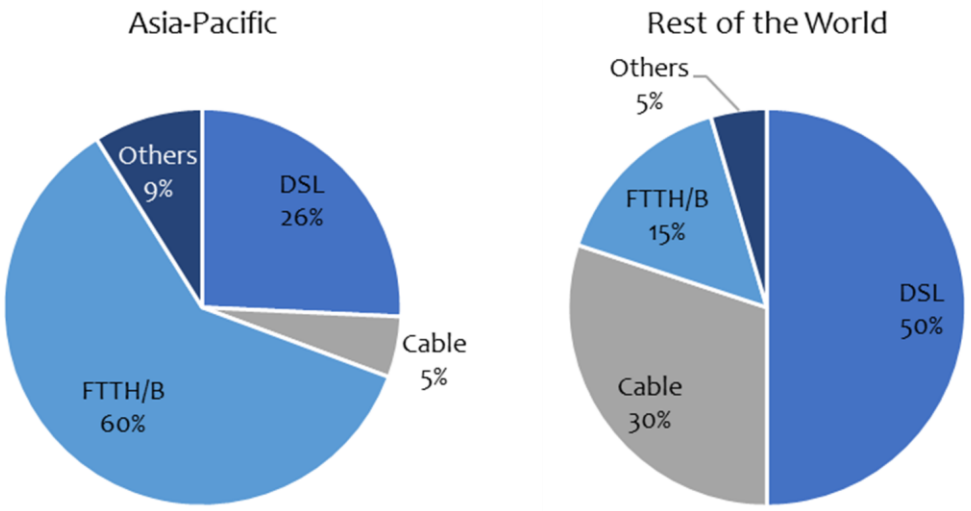
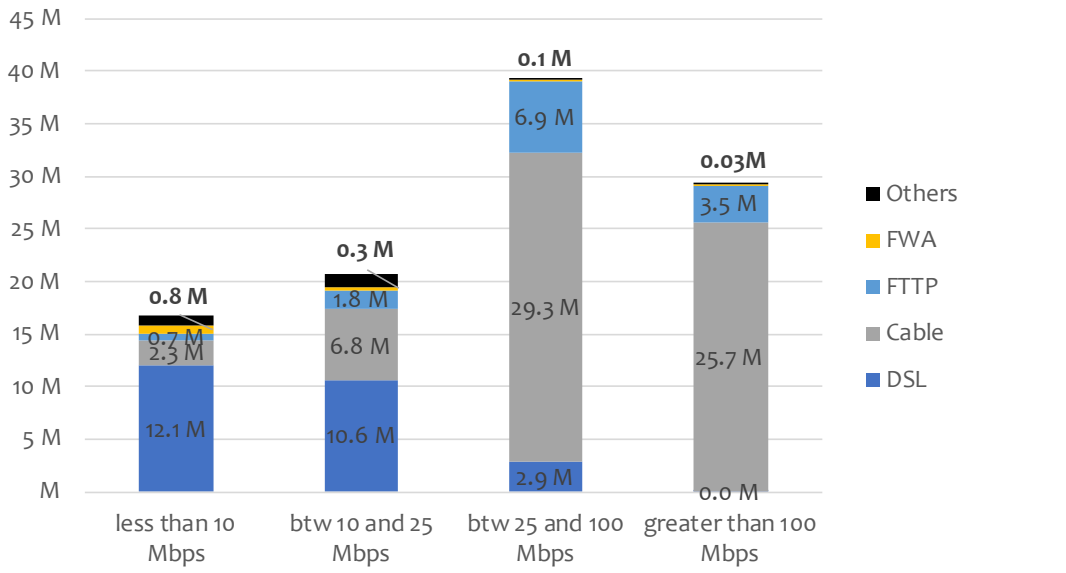


Figure 4. Fixed broadband subscription share by technology

The DSL limitation as an enabling technology for high-speed Internet service can be seen in the fixed broadband connections by technology and speed for the United States. The graph below showcases the FCC broadband data as of June 2017. As clearly delineated, lower speed broadband connections (below 25 Mbps in downlink speed) are mostly served via DSL while higher-speed connections are dominated by cable and fiber. According to this chart, there are about 37 million households in the USA that have fixed broadband connections below 25 Mbps downlink speeds.



Source: FCC (as of June 30, 2017)

Figure 5. USA fixed broadband connections by downstream speed and technology

As the broadband demand increases and cable offerings look to provide "gigabit" speed offers through DOCSIS 3.1 upgrades, these underserved broadband subscribers will likely seek other high-speed broadband connections where available. In some instances where high-speed broadband connections via cable or DSL footprint is not possible (a headend is too far away from subscriber homes to deliver high-speed broadband connections), fixed wireless access may be a good fit.

Cord Cutting - Unbundling of Connectivity and Entertainment

Another key driver of fixed wireless, and broadband service in general, is the rising Internet video consumption. According to the latest Cisco VNI study, the total Internet video traffic is expected to constitute 80% of all Internet traffic in 2021, up from 67% in 2016.[2] In particular, the cord-cutting trend whereby over-the-top video streaming services like Netflix and others are delivered over the Internet is accelerating the demand for high-speed broadband services to view high-definition (HD) and 4K video on multiple devices. The disintermediation of video services independent of the underlying transport network, whether that be cable or satellite TV, is especially impacting the underlying demand for high-speed broadband services in underserved areas in both rural and suburban settings.

It's simple: long-range broadcast TV is no longer attractive to rural people They want to watch the shows on Netflix and Amazon that people are talking about!

[2] Cisco VNI forecast highlights: https://www.cisco.com/c/m/en_us/solutions/service-provider/vni-forecast-highlights.html

Government Broadband Initiatives

The potential impact of Internet connectivity to positively impact people's lives is widely acknowledged by governments and world leaders. To address the large unconnected population around the globe, ITU as a part of its Connect 2020 agenda set a target of 55% of households and 60% of individuals to have access to the Internet by 2020.[3] Over 150 countries have announced their support of this global agenda and have National Broadband Plans in place, including the USA, Brazil, China, India, Australia, and other countries with a large population.

Governments are leveraging different mechanisms to help foster infrastructure investments. For example, in the United States, the Federal Communications Commission (FCC) uses the Universal Service Funds (USF), license conditions, and opening more spectrum for mobile and fixed wireless broadband services. Also, the FCC has established Connect America Fund (CAF) to accelerate a build-out of fixed broadband infrastructure capable of delivering at a minimum, 10 Mbps downlink and 1 Mbps uplink speeds, to unconnected Americans. The FCC has set aside $1.98 B over ten years to subsidize network build-out in areas that are deemed too cost-prohibitive (i.e., too few potential subscribers to make the fixed infrastructure buildout economically unappealing). The CAF II investments for both "25 Mbps downlink and 3 Mbps uplink" and "100 Mbps downlink and 10 Mbps uplink" commitments are expected to roll out in late 2019 and more broadly in 2020.

Similar government funding to subsidize broadband deployments can also be found in Europe and Australia. The European Commission has set aside about €1.0 – 2.0 billion in funding to help subsidize high-speed broadband deployments in underserved areas. It is expected that the funding will be invested in multiple countries by 2021. In some Nordic countries like Norway and Sweden, the governments there are using the public-private investment model in expanding high-speed broadband coverage where market-driven network build-out is not feasible. In Australia, the state-owned National Broadband Network (NBN) is building out wholesale access network using a multitude of technologies including fixed wireless access, fiber, and cable. These government funding models are opening the market opportunity for enterprising operators, both large and small.

In addition to direct subsidy programs like CAF and other USF programs, governments are opening up more spectrum for mobile and fixed wireless applications. To help facilitate high-speed broadband experiences, regulators are opening up hundreds of MHz of licensed and unlicensed spectrum in sub-6GHz and the millimeter wave bands. There is a consensus that 3-4 GHz band will be widely

[3] ITU Connect 2020 agenda targets, https://www.itu.int/en/connect2020/Pages/default.aspx

used for 5G in China as well as the 28-39 GHz band in the USA and Korea for the initial 5G applications, including fixed wireless access. In addition to the unlicensed spectrum available for fixed wireless applications in the 5 GHz and 60 GHz bands, the flexible shared licensing regime like the CBRS in the USA provides an innovative approach to allow access to enterprising fixed wireless providers.

Wireless Internet Service Providers

Wireless Internet service providers (WISPs) are key customers of fixed wireless access equipment. While traditional mobile carriers leverage wireless infrastructure to serve mobile consumers with their smartphones, WISPs use wireless infrastructure to deliver fixed broadband service to homes and businesses. Most WISPs are enterprising regional operators leveraging a combination of a wireless and fixed infrastructure to deliver broadband data, and sometimes voice and other ancillary services, to underserved locations that larger mobile/telco and cable operators have not yet addressed. According to WISPA, an advocacy group for the WISP industry, there are about 3000 WISPs in the United States serving over 3 million subscribers.[4] While there is a no clear count of the total number of WISPs worldwide, Mobile Experts estimates that there are about 10,000 WISPs around the world with some larger players in parts of APAC, Europe, and South America.

Most WISPs in the United States are small to medium businesses serving local communities and regions. With start-up roots, most WISPs leverage unlicensed spectrum and 802.11-based technologies for their fixed wireless networks. A common network consists of a combination of licensed microwave backhaul with unlicensed access points and subscriber radio modules to connect remote homes and business locations. Rise Broadband is the largest WISP in the USA with about 200,000 subscribers. An American WISP serves, on average, 1200 customers while smaller WISPs in rural markets may only count a few hundred subscribers on their networks.[5]

Mobile / Telco Operators

Mobile operators, who are also incumbent telco operators in many countries, are leveraging their LTE mobile networks in regions where fixed broadband infrastructure is either non-existent or aging. The mobile operators are taking advantage of performance improvements in LTE to provide home broadband services to areas where DSL can no longer satisfy the demands for high-speed broadband.

[4] WISP Association (WISPA.org)

[5] The Carmel Group, "The BWA Industry Report 2017" white paper for WISPA

Many LTE fixed home broadband services have already been launched around the globe by mobile/telco operators to strengthen their fixed broadband positions. For example, Airtel-Vodafone in India is selling its *4G Home Broadband* service to address the home broadband needs. Globe in the Philippines has been successfully leveraging its mobile network to improve its market position in fixed business, while at the same time, leveraging the common LTE network for its mobile business. It has signed up over 500,000 home broadband customers since it launched the LTE-based fixed broadband service back in 2015. Meanwhile, Bouygues in France has been selling its *4G Box* service to address the needs in underserved ADSL footprint areas. As the operators continue to adopt LTE Advanced features such as Carrier Aggregation, LAA, etc., the speed performance of LTE fixed wireless services is likely to go up.

Some leading converged/mobile operators are increasingly looking towards 5G for both mobile and fixed use. Some operators view that 5G network can provide sufficient network capacity to handle both the mobile and fixed broadband traffic. For others, the increased network capacity though additional spectrum, massive MIMO, and network densification can provide "headroom" to handle the growth in mobile and fixed traffic. Moreover, they view the use of 5G as a replacement for aging DSL footprints is a good way to justify the 5G capital expenditure. For example, consumers can buy 5G CPEs as an alternative to their fixed broadband needs in China as illustrated below in the e-commerce site, JD.com, which sells Huawei 5G CPE operating in the mid-band.

Source: JD.com

Figure 6. 5G Fixed CPE for sale on JD.com

In the USA, mobile operators have not widely adopted LTE fixed wireless services. Their focus is, first and foremost, serving the growing mobile data traffic. Adding

additional traffic, especially those of home broadband service that consume a lot more GB data than mobile, may damage the overall network performance. Taking the risk of servicing both mobile and home broadband services via a common LTE network may be too big for the mobile operators to take, considering that they derive a 10-40x price premium for mobile traffic over fixed.[6] Moreover, the mobile operators have a smaller share of the fixed broadband market in the USA as cable penetration is high compared to other regions. Nevertheless, many mobile customers now use their "unlimited" plans as a substitute for fixed broadband access, and "mobile only" subscription is a growing trend in the USA.

While the appetite for using LTE network to serve home broadband service is low in the USA, the CAF II funding is generating a lot of interest in fixed wireless access. The favorable economics and possible new spectrum opportunity in the mid 3 -4 GHz band have generated a renewed interest in fixed wireless technologies. Some operators are readily deploying fixed wireless access to meet its CAF commitment. For example, AT&T is using its WCS spectrum as a dedicated carrier to provide "10 Mbps down/1 Mbps up" fixed broadband service to homes and businesses in rural communities as a part of its CAF commitment. AT&T's Fixed Wireless Internet service is expected to reach 400,000 locations in 8 states by the end of 2017 and over 1 million locations by 2020. While AT&T can deploy fixed wireless service readily using its licensed spectrum, many telcos without licensed spectrum will be keen to leverage unlicensed or less expensive shared spectrum fixed wireless technology. With the government support of several hundred million dollars each, AT&T, CenturyLink, Frontier, and Windstream are expected to seriously consider fixed wireless access as a part of their technology toolset in delivering the mandated 10/1 and 25/3 Mbps broadband speeds to "eligible locations" in rural America.

[6] Author's blog on "mobility premium" trend: https://www.fiercewireless.com/wireless/industry-voices-mun-mobile-pricing-drops-from-9-gb-to-1-80-gb-just-1-year

Nationwide Summary

PC Carrier	Eligible Locations	Support Amount
AT&T	1,265,036	$493,973,528
CenturyLink	1,190,016	$514,334,051
Cincinnati Bell	7,084	$2,229,129
Consolidated Communications	24,698	$13,922,480
Fairpoint Communications	106,380	$38,193,432
Frontier Communications	659,587	$283,401,884
Hawaiian Telcom Inc	11,081	$4,424,320
Micronesian Telecom	11,143	$2,627,177
Verizon	387,470	$143,924,995
Windstream Communications	413,345	$178,779,073
Total	**4,075,840**	**$1,675,810,069**

Source: FCC

Figure 7. CAF II eligible locations and support funding to respondent carriers

Over-the-Top Competitive Carriers

Besides the WISPs and mobile/telco operators, another class of operators is taking great interest in fixed wireless access. These so-called "over the top" (OTT) competitive carriers view broadband connectivity as an adjacent market opportunity that also enhances their primary businesses. With favorable market developments in technology, spectrum, and economics, OTT carriers see fixed wireless access as a possible means to create the broadband connectivity business. Some example companies in this category include Google, Vivint, Amazon, Dish, and cable operators. Even though Google's broadband ambition has cooled considerably since the early days of Google Fiber, and more recently its Webpass acquisition in 2016, we believe fixed wireless access will remain a credible technology option for OTT carriers to opportunistically get into the fixed broadband business.

4. TECHNOLOGY OPTIONS

All fixed wireless access (FWA) technologies aim to maximize distance reach and throughput capacity at low cost. To achieve this lowest possible "cost per bit" economics, various fixed wireless technologies and proprietary vendor solutions incorporate different spectrum and interference mitigation strategies to offer low "cost per GB" access system to service providers.

In this report, we broadly categorize fixed wireless access (FWA) technologies into the following categories:

- *802.11-based* (proprietary) – proprietary solutions operating in unlicensed, shared, and lightly licensed spectrum bands;
- *3GPP-based* (LTE and 5G) – based on global standard and ecosystem of LTE and 5G on dedicated or shared licensed spectrum bands for FWA;
- *Disruptive new ideas* – aerial FWA via balloons or drones (e.g., Google's Project Loon).

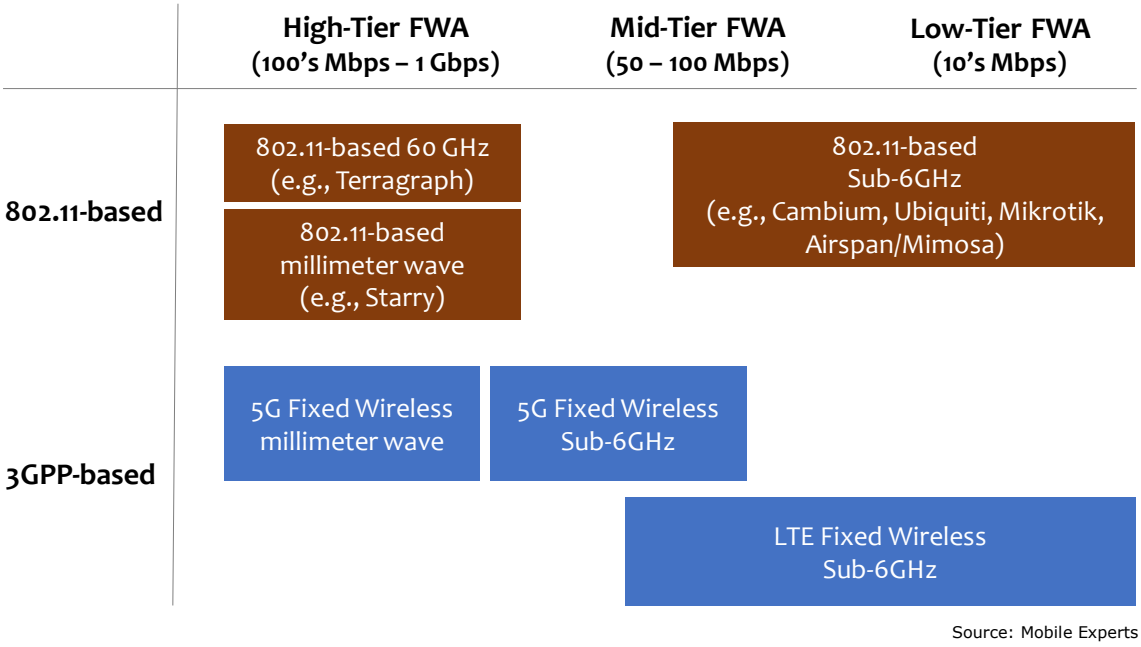


Figure 8. Both 802.11- and 3GPP-based technologies can address the different FWA tiers

While both the 802.11-based proprietary and 3GPP-based LTE and 5G technologies can address the high, mid, and low-tiers of the fixed wireless access market, the mobile operators generally favor the standards-based LTE and 5G fixed wireless solutions.

Smaller WISPs and OTT competitive carriers generally prefer the 802.11-based solutions operating in the unlicensed or lightly-licensed spectrum bands. Meanwhile, some regional Telcos are expected to leverage both the 802.11-based and 3GPP-based fixed wireless solutions based on target markets and spectrum availability.

802.11-based Approach to Fixed Wireless

The 802.11-based unlicensed radio products were instrumental in the creation of the fixed wireless market. Inexpensive unlicensed radios enabled enterprising companies to cost-effectively build wireless transport networks to connect unconnected or underserved rural markets. Previously, attempts to lay broadband wireline infrastructure were uneconomical, so FWA was generally picked up by entrepreneurs on a tight budget. Companies like Ubiquiti, Cambium, and others were instrumental in producing low-cost point-to-point (PtP) backhaul and point-to-multipoint (PtMP) access point and subscriber unit products to jump-start the market.

In the early days, companies took low-cost Wi-Fi chipset solutions and customized MAC layer 2 and above to create proprietary solutions specifically designed for fixed wireless access and transport. In general, 802.11-based proprietary fixed wireless solutions have added the following features to overcome some of the key drawbacks of Wi-Fi standard:

- *Coordinated Scheduling (TDMA/TDD)* – A key drawback of Wi-Fi chipsets is that the Wi-Fi standard uses contention-based CSMA/CD in which all devices compete for over-the-air resources until they succeed. In this "uncoordinated" fashion, a lot of airtime is wasted when packet collisions occur between AP and CPEs. Some vendor solutions correct this by creating a TDMA/TDD framework so that the packet delivery between AP and subscriber CPEs can be coordinated.

- *"GPS Sync"* – Many 802.11-based fixed wireless solutions have now adopted this feature to have all AP's to transmit at the same time, and then receive data from CPE's at the same time as well. This way, possible interference between AP's on the same channel can be mitigated. Also, the GPS Sync essentially allows frequency reuse in a scenario where four AP's are deployed at a site, in 90-degree sector configuration. Instead of using four separate channels at the site to avoid self-interference, one can use two channels (channels A and B) where one set of "back to back" AP's (in the 4-sector site) use the channel A while the other set of "back to back" AP's use the channel B thus "saving" spectrum.

- *Multi-User MIMO (MU-MIMO)* – The MU-MIMO operation essentially allows an AP to steer simultaneous beams to different users with each beam containing specific packets for the intended client user. It effectively increases capacity and offers higher speed per user. While the 802.11ax standard defines a maximum number of MU-MIMO transmissions to eight, some vendor solutions have taken this to a higher order. For example, Cambium's cnMedusa product supports 14x14 MU-MIMO.

Instead of the "brute force" method of applying wider channels (more spectrum) or higher modulation (e.g., 256 QAM) to overcome the inefficiencies of 802.11 standards, these "coordination" features allow more efficient usage and allocation of airtime.

To make necessary customizations, 802.11-based proprietary fixed wireless product companies have strategic relationships with Wi-Fi chipset companies. For example, Mimosa Networks (now Airspan) uses Quantenna's (now ON Semiconductor) Wi-Fi chipset in its product while Starry's millimeter wave product is believed to be based on Marvell's Wi-Fi chipset solution. Some have chosen to create their own chipset solution using FPGAs to truly create a custom fixed wireless solution. A good example is Cambium, whose PMP 450 platform is considered one of the more robust fixed wireless solutions in the market. To compete against low-cost vendors like Ubiquiti and Mikrotik, Cambium also offers a Wi-Fi chipset-based solution called ePMP, which has fewer features than its flagship PMP 450 product.

Although most 802.11-based proprietary solutions start with a low-cost Wi-Fi chipset solution that may be 5-6x cheaper than LTE at the chipset level, many proprietary vendors take on the additional R&D cost of making customizations on top of standard "merchant" silicon. In some respects, the 802.11-based proprietary vendors have limited scale to drive down the cost of their equipment at scale, especially CPEs. It's a bit ironic that proprietary 802.11-based solutions are protected from commoditization because they're customized, but it's also difficult to achieve cost reductions. In this way, the 802.11 based vendors have a difficult time selling to large-scale operators, where overall ROI is primarily driven by the CPE cost (see the section on "*Unit Economics of Cost to Pass and Cost to Connect*" below).

802.11ax (Wi-Fi 6) for Fixed Wireless

The 802.11ax, or now referred to as "Wi-Fi 6" in marketing jargon, promises to greatly improve efficiency for high-density connections. In other words, it offers higher capacity and more connections, especially in dense deployments. The net performance improvement translates to 4x increase in capacity compared to 802.11ac and improved coverage. The higher efficiency is achieved from a few key features found in 802.11ax, including:

- 8x8 MU-MIMO on both the 2.4 and 5 GHz bands – increase capacity
- OFDMA – improves network efficiency and reduces latency
- Scheduled access
- WPA3 security

One key aspect of 802.11ax is that it operates in both 2.4 and 5GHz bands. Hence, the performance improvements of Wi-Fi 6 can improve the radio link of 2.4GHz fixed wireless solutions in the field – thus providing better reliability and speed. The increase in the number of subcarriers, larger OFDM FFT sizes, narrower subcarrier spacing, and longer symbol time, in aggregate, improves robustness and efficiency while keeping the data rates the same as 802.11ac. In fact, with higher modulation support for 1024 QAM, the 802.11ax provides a higher maximum data rate. More importantly, though, it provides higher efficiency in multipath fading environments, which is a key benefit in outdoor operation.

Like 802.11ac, 802.11ax devices use explicit beamforming to direct data packets simultaneously to multiple users who are spatially separated. While the 802.11ac only defined MU-MIMO on the downlink, the 802.11ax standard defines uplink multiuser mode as well in which simultaneous data transmission from multiple client devices to an access point is possible. Another key addition of the 802.11ax standard is that it has defined two different ways of multiplexing users: Multiuser MIMO (MU-MIMO) and Multiuser Orthogonal Frequency Division Multiple Access (MU-OFDMA). In essence, 802.11ax borrows the underlying OFDMA technology used in LTE base stations to centrally manage multiple client devices, thus enabling more efficient access to a radio channel.

In MU-OFDMA operation, specific sets of subcarriers can be allocated to different users over time. This is the same scheme that LTE uses in the allocation of physical resource blocks for multiple users. Borrowing a similar LTE terminology, the 802.11ax defines the smallest subchannel as a Resource Unit (RU), with a minimum size of 26 subcarriers. As noted in the figure below, an access point can allocate the entire (20/40/80/160 MHz) channel to only one user at a time as is currently done in 802.11ac, or it can "chop up" the frequency (in RU) and allocate specific sets of RUs to different users over time.

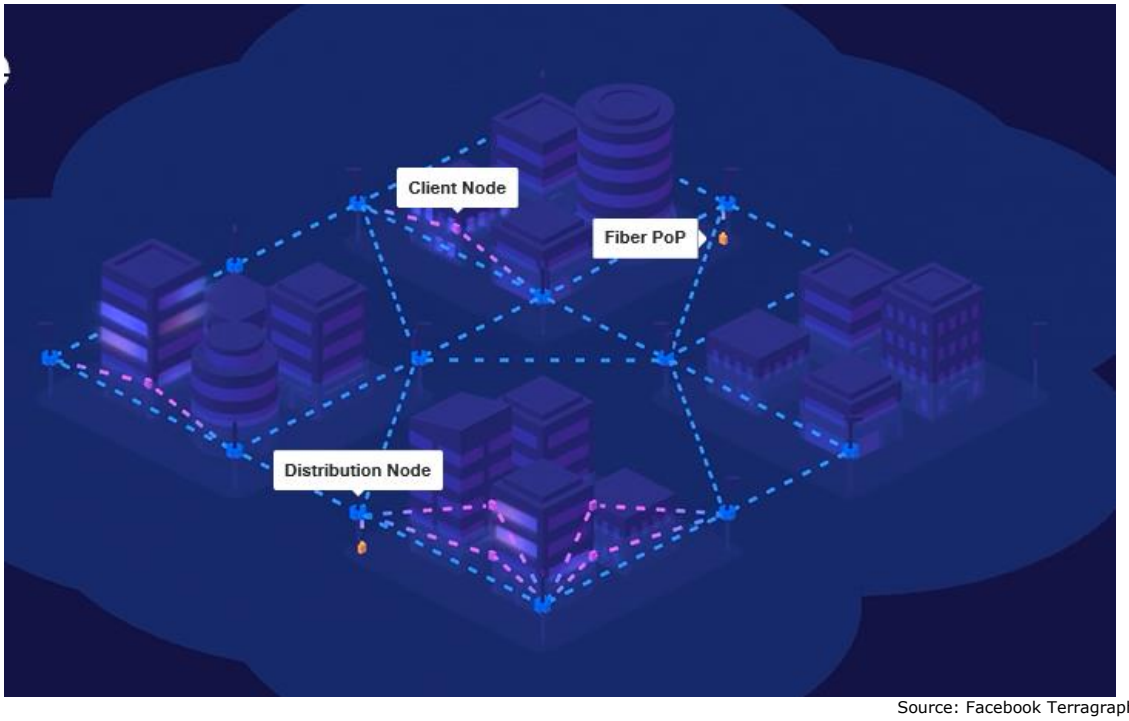
Also, the resource scheduling in the uplink increases efficiency by moving away from contention-based resource allocation found in 802.11ac to scheduling approach (like LTE). With a combination of downlink and uplink MU-MIMO and MU-OFDMA, the 802.11ax is expected to support four times the average user throughput. With combinations of these techniques and higher physical data rates, 802.11ax is expected to improve user throughput and extend coverage with higher 8x8 MIMO, especially in dense environments, which has been an Achilles' Heel for Wi-Fi relative to LTE. Note that the MU-OFDMA and resource scheduling will improve contention

between clients that share an access point, but not for users on different access points.

802,11 ad/ay and Terragraph

The 60 GHz unlicensed technology has been around for many years as 802.11ad WiGig. Under the Wi-Fi Alliance management, the 802.11ad WiGig technology has been positioned as a "multi-gigabit Wi-Fi" technology for short-range applications such as wireless connectivity for VR headsets, HDMI/USB replacement, and so on. In the carrier space, 60 GHz 802.11 ad/ay solutions are sometimes found in short-range (~200 meters) wireless backhaul applications.

Facebook's Terragraph project has taken the banner of establishing an ecosystem of leveraging the 60 GHz unlicensed spectrum to create fiber-replacement technology solution for multi-gigabit wireless connectivity solution for urban areas. Qualcomm is the major 60 GHz chipset supplier for the Terragraph project. It is expected that Qualcomm will soon deliver the 802.11ay/Terragraph chipset, possibly the later part of 2019. Cambium, Mikrotik, Siklu, and RADwin are key OEM suppliers looking to introduce "gigabit" 60 GHz PtMP products for fixed wireless access applications in the urban markets.



Source: Facebook Terragraph

Figure 9. Facebook Terragraph 60 GHz PtMP Network Architecture View

Terragraph enhances the standard 802.11 ad and 802.11ay features to improve efficiency in large deployments. Some of the key attributes of Terragraph include:

1. TDD/TDMA enhancement for MAC efficiency;
2. Extended range to over 200 meters;
3. Layer 3 meshing for higher reliability; and,
4. IPv6 internetworking.

A key benefit of 60 GHz spectrum is the ultrawide channel – 2.16 GHz channel spacing! A whole lot can be transmitted in that amount of spectrum. Local regulatory bodies determine regional spectrum allocation from the total of six channels:

- USA: 57.0 – 71.0 GHz (6 channels available)
- Europe: 57.0 – 66.0 GHz (2 channels available)
- China: 59.0 – 64.0 GHz (2 channels available)
- S. Korea: 57.0 – 64.0 GHz (3 channels available)
- Japan: 57.0 – 66.0 GHz (4 channels available)
- Australia: 59.4 – 62.9 GHz (just shy of 2 channels available)

Due to the physical limits of RF propagation at the 60 GHz band, the range is fairly short – typically 200 meters in point-to-point wireless backhaul applications although we have seen some vendors claiming even longer distances.

802.11ay is the next-generation 60 GHz technology that further extends the transmission speed and range. According to the draft specification, the standard proposes to support 20-30 Gbps transmission rate and extend the range to 300-500 meters. These improvements are expected to be achieved through:

- Up to 4 channel bonding (each 802.11ad channel uses a maximum of 2.16 GHz bandwidth), yielding a maximum bandwidth of 8.64 GHz
- MIMO with a maximum of 4 spatial streams (a link rate per stream is 44 Gbps; thus with 4 streams, this can go up to 176 Gbps)
- High-order modulation scheme, possibly up to 256 QAM

With the tremendous amount of spectrum already available in the 60 GHz unlicensed spectrum, the need for channel bonding for a higher throughput capacity may not be warranted in most use cases. The coverage reach may be a more important factor, generally in fixed wireless access.

For the carrier space, however, it will likely be used only for fixed wireless access and backhaul applications in a dense urban environment. For the fixed wireless application, the CPE cost is a major determinant of a viable business case. While the ecosystem is making great strides, we believe the market is still about 1-2 years out.

The Terragraph ecosystem may provide enough scale and technology advancements to allow the 60 GHz point-to-multipoint market to flourish a bit sooner.

LTE Fixed

As the 3GGP technology evolves towards 5G, LTE continues to deliver. With Carrier Aggregation, 4x4 MIMO, and 256 QAM modulation combinations, LTE can reach a peak throughput capacity of 1 Gbps using only 60 MHz of spectrum. This implies that using an over-subscription factor of 10:1, an LTE small cell supporting 100 subscribers can theoretically provide ~100 Mbps per user at a "Gigabit LTE" site. With the aggregation of unlicensed spectrum with LAA, the business case for LTE Fixed improves even further as operators can tap the unlicensed spectrum for data capacity while managing the quality of service through control signaling on the primary carrier in the licensed spectrum.

LTE with massive MIMO (64T64R) can deliver a significant capacity boost. As shown below, Huawei has successfully managed to deliver close to 100 Mbps LTE fixed wireless broadband service using 40 MHz of spectrum, massive MIMO, and 2T4R LTE CPE's. With additional spectrum bandwidth coming available in the sub-6 GHz[7] and 28/39 GHz band, Huawei believes that fixed wireless offers the incremental market opportunity for its core service provider customers. The company is positioning massive MIMO on base station AP's and high-order MIMO on CPE's to extend the range and capacity of fixed wireless systems. As the leading vendor of LTE and 5G CPE's, Huawei already offers 5G CPEs for sale in China.

Source: Huawei

Figure 10. LTE and 5G performance improvements provide lower cost-per-bit transport

[7] likely the 3-4 GHz band positioned for 5G in China, Europe and other regions

5G Fixed

With larger chunks of spectrum in the mid-band (3 - 4 GHz) and the millimeter wave (24 -40 GHz) bands and lower latency capability, 5G offers the tremendous option for fixed wireless application. The use of massive beamforming at high millimeter wave frequencies makes it easier to provide coverage, especially in the fixed wireless context, since narrow beams can be directed to fixed locations unlike in the mobile case. Moreover, the MU-MIMO operation allows the signals from multiple CPEs to be multiplexed simultaneously on the same channel in different beams, thus providing greater spectral efficiency and high peak throughput capacity which yields higher user speeds. With large spectrum bandwidth available in the millimeter wave bands, 5G fixed wireless promises "gigabit" user speeds.

While the much of the press coverage in the USA has evolved around Verizon's 5G Home service using the 28 and 39 GHz bands using a total of 800 MHz of spectrum, the real action on 5G fixed wireless is happening in the 3-4 GHz mid-band elsewhere. Some leading operators are looking towards spectral efficiency of 5G NR, additional spectrum (up to 100 MHz of mid-band spectrum in some markets), and massive MIMO gain to provide "wide and deep" network capacity layer. As fixed broadband usage appears to be waning in some markets, major mobile operators, who are also incumbent fixed telco operators in many markets, are opting to share the increased mobile network capacity towards fixed wireless broadband services.

Indoor vs. Outdoor CPE

Operating above 20 GHz, the placement of the subscriber CPE antenna will be critical in achievable range, and consequently cell edge performance. According to Ericsson, a base station above clutter (on the tower above tallest trees) provides the best range while placing CPE antenna above the roof at subscriber homes provides the best result since such deployment yields higher line-of-sight probability between the CPE antenna and the base station AP. The relative cell range between 3.5 GHz and 28 GHz bands is about 10x difference, as shown below.

Cell range	Base Station AP above the clutter		Base station AP below the clutter	
	3.5 GHz	28 GHz	3.5 GHz	28 GHz
Indoor CPE antenna	2.5 km	250 m	1.8 km	180 m
Outdoor CPE antenna	5 km	500 m	2.5 km	250 m
Rooftop CPE antenna	100 km	10 km	3.5 km	350 m

Source: Ericsson Technology Review, "5G and Fixed Wireless Access," Dec 2016

Figure 11. Impact of AP and CPE antenna placement on FWA cell range

It should be noted that the millimeter wave band with more capable CPE and outdoor antenna placement can extend the range and coverage of a FWA system, even in the millimeter wave case.[8] This is yet another tradeoff that a service provider or a system designer can make – i.e., leverage a costly CPE to extend range and throughput, or a cheaper CPE and operate at a shorter range and coverage.

Disruptive New Ideas: Aerial Fixed Wireless Access

Some new disruptive ideas and projects have been introduced by some major Internet companies like Google and Facebook in recent years. Google's Project Loon and Facebook Drone projects propose to use several large balloons and drones respectively, fitted with fixed wireless radio gear onboard to "beam" fixed wireless links down to earth. While these ideas are disruptive and continue to advance in their capabilities and features, the economic viability is uncertain -- especially when you consider the potential revenue opportunity from the unserved market segment against the operational expenses of maintaining such complex infrastructure systems in the air. Because the commercial deployments of these new ideas are still in the early stages, the potential contributions of fixed wireless access equipment from this segment is not tracked in this report.

Source: Facebook, Google

Figure 12. Aerial Fixed Wireless Access – Google Loon, Facebook Drone

[8] Mobile Experts believes that Starry has purposely designed its system to operate at maximal range and coverage at the millimeter wave band (~1 km at 37 GHz) which requires a complex and costly CPE (vs. a system that operates at a shorter range and coverage but requiring less expensive CPE).

Deployment Architecture: 'Tower' vs. 'Micro Hub'

Fixed wireless operators can target varying market density environments with different deployment architectures to minimize the cost-per-bit economics. As noted earlier, major cost elements in a fixed wireless access system include:

- Base station access point (AP)
- Customer premise equipment (CPE), or subscriber modules
- Spectrum (if the licensed band is utilized; $0 for unlicensed)
- Site cost ("tower" lease)
- Backhaul (fiber or wireless backhaul link cost)

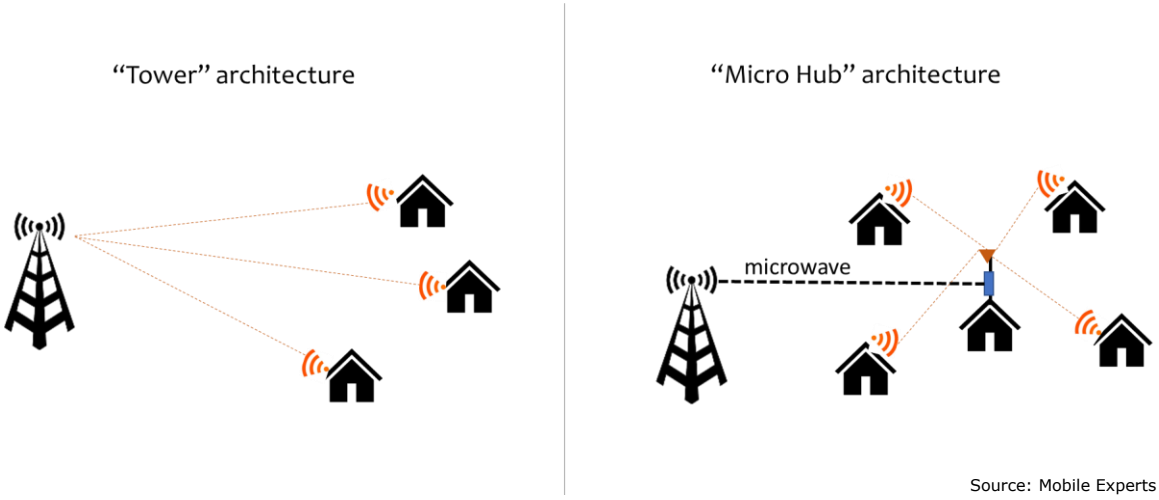


Figure 13. "Tower" vs. "Micro Hub" architecture

Most fixed wireless systems in rural markets employ the traditional "tower" architecture whereby a PtMP radio on a tower serves multiple subscriber radios. While this makes sense in rural markets where operators look to optimize for coverage to pass as many homes and businesses in sparsely populated areas, the "tower" architecture becomes uneconomical in denser suburban or urban settings. In order to provide competitive high-speed broadband service in denser markets (50-100 Mbps in the USA), fixed wireless networks need to be densified. The higher number of sites, if they can even be acquired expeditiously, and associated backhaul, adds cost. To address this, some operators and vendors are advocating what we call "micro hub" architecture (named after the "hub and spoke" concept).

In the "micro hub" architecture, the placement of PtMP radio happens at one of the homes in a neighborhood (under a reciprocal commercial arrangement whereby the "hub" homeowner gets free broadband service instead of placing the PtMP radio and antenna on his/her rooftop) instead of on a tower. The "hub" home would be

connected wirelessly to a tower that aggregates backhaul traffic from multiple hubs, which is then fed up to an Internet PoP. At each "hub" home, a PtMP radio could serve a limited number of subscribers using unlicensed spectrum with either 802.11-based or LTE fixed technology.

Choosing between 802.11-based and 3GPP-based FWA

Both 802.11-based and 3GPP-based fixed wireless technologies can enable different "speed vs. reach" combinations for rural, suburban, or urban settings based on spectrum and deployment architecture selections as illustrated below.

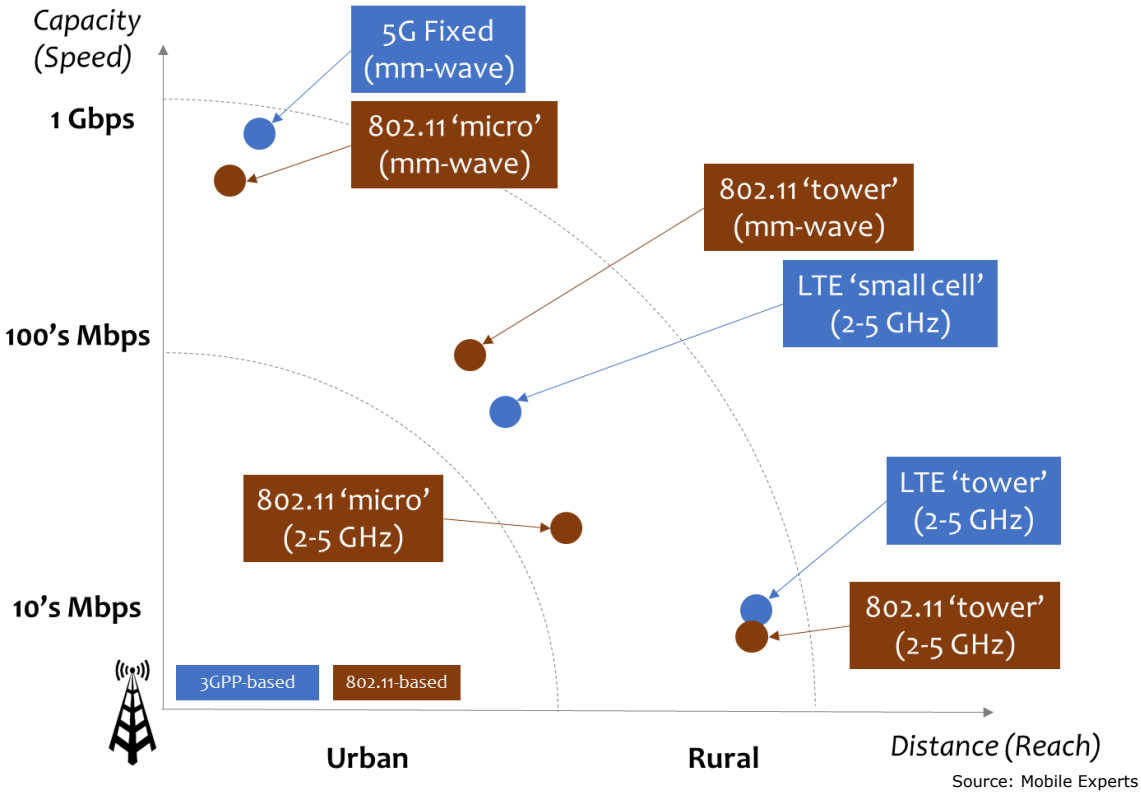


Figure 14. Technology, spectrum, and architecture to optimize speed and reach

Spectrum selection is a primary determinant of the "speed vs. reach" tradeoff in a fixed wireless system. To reach higher user speeds, more spectrum is needed. And, large chunks of channel bandwidth are mostly found in the higher millimeter wave bands. However, the higher frequency bands have shorter reach due to high attenuation. Thus, the use of millimeter wave bands will likely be confined to denser suburban or urban environments. Meanwhile lower frequency bands will be preferred in sparsely populated rural markets where the design goal is to maximize reach and coverage.

Deployment architecture and antenna placement can also impact the speed vs. reach tradeoff. A traditional deployment architecture where a base station is mounted on a tower above the clutter provides a maximal reach and coverage. In contrast, placing a base station below the clutter, on top of a "hub home" or utility pole, for example, can limit the range of fixed wireless AP. If the design goal is to densify the network to effectively increase user speeds by limiting the sector capacity available to fewer users, then the "micro hub" deployment may be suitable. Otherwise, traditional tower architecture provides the best coverage, especially at lower bands.

5. SPECTRUM LANDSCAPE

All fixed wireless access technologies aim to maximize distance reach and throughput capacity at low cost. To achieve this lowest possible "cost per bit" economics, various fixed wireless technologies and proprietary vendor solutions incorporate different spectrum and interference mitigation strategies to offer low "cost per GB" access system to service providers.

Spectrum is Key

Spectrum choices for fixed wireless access span across from sub-1 GHz to 70/80 GHz millimeter wave bands. This wide range of spectrum options come with caveats on distance reach and speed performance, AP-CPE cost tradeoffs, "$/GB" transport cost, architecture/deployment choices, core network requirements, and many other factors that impact on-going operations of delivering fixed wireless broadband service. One thing is clear. Spectrum is a key determinant of broadband service level (speed and quality), and cost at which that service is delivered.

Spectrum Band	Bandwidth	License Regime	Technology	Interference Risk
900 MHz (902 - 928)	26 MHz	Unlicensed	802.11 (proprietary)	High
2.4 GHz	~80 MHz	Unlicensed	802.11 (proprietary)	High
2.5 GHz	194 MHz	Licensed	3GPP (LTE)	Low
3.5 GHz (3.55 - 3.7)	150 MHz	Shared (CBRS)	3GPP (LTE), 802.11 (proprietary)	Medium (GAA)/ Low (PAL)
5 GHz (5.15 - 5.85)	580 MHz	Unlicensed	802.11 (proprietary), LTE (proprietary)	High
6 GHz (5.925 - 7.125)	1200 MHz	??	802.11, LTE/5G ?	High
28 GHz	850 MHz	Licensed	802.11 (proprietary), 3GPP (5G)	Low
39 GHz (37 - 40)	3 GHz	Licensed (37GHz), Shared (39GHz)	3GPP (5G), 802.11 (proprietary)	Low
60 GHz (57 - 71)	14 GHz	Unlicensed	802.11 (WiGig)	Medium

Source: Mobile Experts

Figure 15. Spectrum options for fixed wireless access

Fixed wireless broadband service delivery over a licensed band is preferred of course since interference risk is inherently non-existent through the license, but this adds cost (spectrum and higher base station AP cost). Moreover, leveraging wide spectrum blocks such as the 5GHz and millimeter wave bands can provide very high throughput capacity, thus higher broadband speeds, but they are prone to interference risk in the case of using the 5GHz unlicensed band, and smaller coverage in the case of using the millimeter wave bands. Optimizing these tradeoffs along with assessing market demand and competition is key to success in fixed wireless access.

900 MHz

The 900 MHz fixed wireless access systems are often found in far rural deployments where distance reach is paramount to making the business case work. Fixed wireless service providers primarily use this band to take advantage of the far-reaching RF propagation characteristics of this band. Due to the limited spectrum in this band, however, the throughput capacity or speed offered to customers is limited to tens of Mbps at best. Operators sometimes need to consider interference mitigation strategy in case there are other unlicensed products (IoT devices, wireless microphones, etc.) using the same band nearby. With the longer reach, the probability of interference is often higher.

2.4 GHz Unlicensed

Similar to the 900 MHz band, WISPs have used the 2.4 GHz band in the past to take advantage of a larger chunk of spectrum bandwidth in this band. With the popularity of Wi-Fi use indoors and out, the rising noise floor in this spectrum has made its usage problematic in the past. With most Wi-Fi indoor usage moving to the 5 GHz band, some operators are coming back to the 2.4 GHz band as the noise floor has come down somewhat to make this more useful. Like the 900 MHz band, this band is most often used in very rural areas to reach far away subscribers from a base station access point.

2.5 GHz Licensed

The 2.5 GHz band is comprised of Educational Broadband Service (EBS) and Broadband Radio Service (BRS) bands, totaling 194 MHz of usable spectrum within the 2495 – 2690 MHz band. With the FCC rule change in mid-2000s, the EBS and BRS licenses now allow two-way mobile and fixed data services. While Sprint holds the bulk of these licenses throughout the USA, some smaller operators use this band to provide fixed wireless services. Some are still utilizing WiMAX-based technology in this band, but many operators now look to TD-LTE for future deployments.

In July 2019, the FCC made the following rule changes to "modernize the outdated regulatory framework for the 2.5 GHz band" including:

- Eliminated restrictions on the types of entities that can hold licenses;
- Removed the educational use requirements but preserved incumbent private lease agreements;
- Provides bidding credits for smaller WISPs, small businesses, and Tribal lands;
- Adopted county-size license areas to incentivize rural WISPs to participate in the competitive auction;
- Adopted 3 spectrum band plans – two 50-MHz blocks and one 16.5 MHz block;

It is expected that the 2.5 GHz spectrum band under the new rule changes will be highly sought by WISPs and Telco operators for fixed wireless access. This spectrum will likely become available in late 2020 for commercial deployment.

3.5 GHz Shared (CBRS)

The *Citizen Broadband Radio Service* (CBRS) provides for shared spectrum use in the 3.5 GHz band. For the first time, dynamic spectrum sharing rules based on the three-tier licensing regime (as shown below) allows commercial use of the band while ensuring interference protection and uninterrupted use by the incumbent users (i.e., military radars and fixed satellite stations). Under the plan, a *Spectrum Access System* (SAS) maintains a database of all CBRS base stations and coordinates spectrum access among the incumbent and new commercial users. In the three-tier licensing structure, at least 80 MHz of the spectrum are designated as *General Authorized Access* (GAA), or unlicensed use, and up to 70 MHz of *Priority Access License* (PAL) are planned to be auctioned off as licensed band shortly.

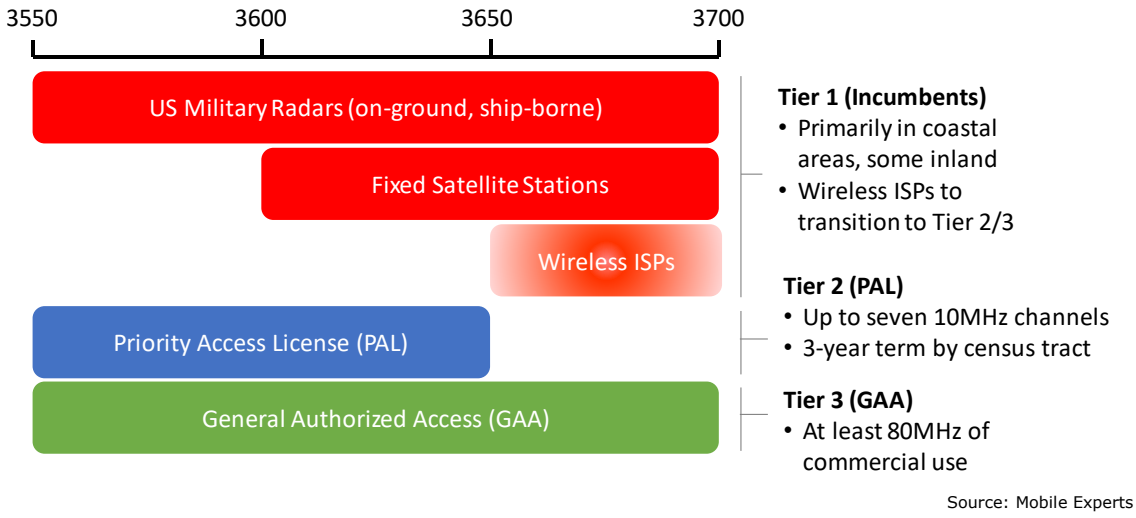


Figure 16. CBRS shared spectrum licensing framework

It should be noted that many WISPs currently use the 3.65 – 3.7 GHz band as temporary "incumbent" users for fixed wireless. By 2020, the use of this particular portion of the band will need to transition under the CBRS three-tier licensing regime.

3.7 – 4.2 GHz

With a great interest in the 3.5 GHz CBRS band from many powerful mobile operators and cable providers, there is an effort to open up access to the 3.7 – 4.2 GHz band for FWA. This effort is being led by the Broadband Access Coalition, comprised of many notable companies and organizations in this field, including WISPA, Mimosa Networks, New America Foundation, Rise Broadband, Cincinnati Bell, and others. Moreover, other major companies, including Frontier, Windstream, Starry, Google, and Microsoft, are backing this lobbying effort to open up 500 MHz of additional spectrum adjacent to the CBRS band. The FCC will need to decide whether this band should be licensed for mobile, shared (as with CBRS), or structured in another way. Outside of the USA, many governments are looking at this band for potential 5G services. So far, the direction of this band in the USA is unclear.

5 GHz Unlicensed

For many WISPs, the 5 GHz band has been the "workhorse" of delivering fixed wireless broadband access with relatively large amounts of bandwidths available across several different frequency band ranges with different usage requirements. For fixed wireless application, many WISPs use "U-NII-2-extended" and "U-NII-3" bands for different reasons. With dynamic frequency selection (DFS), or radar avoidance, requirement, many common Wi-Fi access points typically do not use the "U-NII-2-extended" band. Thus, it is relatively "pristine" unlicensed spectrum upon which to deliver fixed wireless access, especially for operators targeting denser suburban settings.

Moreover, this particular band is considered a "worldwide" band as it is designated as unlicensed globally. Hence, it provides a greater market opportunity for vendors to address the global market. Unlike the U-NII-2-extended band, the U-NII-3 band provides a greater transmit power limit. Hence, this is popular among traditional WISPs looking to maximize reach, especially in rural areas where the business case mandates a maximal coverage.

Band	Freq. Range	Bandwidth	Max. transmit power	Max. EIRP
U-NII-1	5.15 – 5.25 GHz	100 MHz	50 mW	200 W
U-NII-2A	5.25 – 5.35 GHz	100 MHz	250 mW	1 W
U-NII-2B	5.35 – 5.47 GHz	120 MHz	Not used in unlicensed access	
U-NII-2 extended (*)	5.47 – 5.725 GHz	255 MHz	250 mW	
U-NII-3	5.725 – 5.85 GHz	125 MHz	1 W	200 W

Source: Mobile Experts

Figure 17. 5 GHz unlicensed U-NII band ranges

6 GHz

Wi-Fi proponents are eager to tap into a wide swath of new spectrum in the 6 GHz (5925 – 7125 MHz) band. Leading companies including Qualcomm, Broadcom, Cisco, WISPs, and others are proposing to "open up" the band for the unlicensed use, similar to the adjacent 5 GHz band which has been a workhorse for the Wi-Fi industry and the WISP fixed wireless broadband services. The band is primarily used today by "Fixed Service" and "Fixed Satellite Service" earth station uplink services related to cable TV services, in addition to some mobile services (i.e., BAS, CARS, LTTS, and OFS) in certain portions of the band. The proponents argue that the Fixed Service operations are high-power, highly directional, outdoor applications which can be well-coordinated with mostly indoor Wi-Fi operations at lower output power. The group is proposing to segment the 6 GHz band (in a similar manner to the 5 GHz band) into multiple U-NII bands as follows in order to protect specific incumbent users of the band.

Band	Freq. Range	Bandwidth	Incumbent use	Max. EIRP
U-NII-5	5.925 – 6.425 GHz	500 MHz	Fixed Satellite uplink	??
U-NII-6	6.425 – 6.525 GHz	100 MHz	Mobile BAS, CARS, LTTS, OFS	??
U-NII-7	6.525 – 6.875 GHz	350 MHz	Not used in unlicensed access	??
U-NII-8	6.875 – 7.125 GHz	250 MHz	Mobile BAS, CARS	??

Source: Mobile Experts

Figure 18. Proposed 6 GHz unlicensed U-NII band designation

Wi-Fi proponents are arguing for less restrictive UNII-3 like regulation, thus permitting diverse applications from outdoor fixed wireless to indoor enterprise wireless networking. Some major operators like AT&T have sounded the alarm in unlicensed use in the band, stating critical infrastructure use in the band. It is unclear as to how the FCC will decide in the fate of the unlicensed use of the 6 GHz band. IEEE 802.11ax users have already presumed that they can operate in this particular band under the proposed U-NII rule. Gaining even portions of the 6 GHz band will be a windfall for the Wi-Fi proponents. If major carriers concede some portions of the band for unlicensed use, Carrier Wi-Fi deployment for indoor applications through CPE will certainly take advantage of the spectrum if and when that happens.

The potential use of the 6 GHz unlicensed band for outdoor fixed wireless use will require some database management for coordination with incumbent users, but it is likely that rural operators will seek a simpler spectrum management system as compared to the SAS model adopted in the CBRS band.

28-39 GHz Licensed

The 28-39 GHz band is often perceived as the 5G band, especially in the United States where operators are competing to launch the first "5G" network. With recently acquired 28 and 39 GHz bands from XO and Straightpath, Verizon is looking to put these spectrum assets to work through 5G fixed wireless service. Although Verizon's initial fixed wireless service has leveraged its homegrown 5GTF specification, the network is already being upgraded to 3GPP 5G NR fairly quickly. As the mobile ecosystem works towards enabling true mobile use of these high spectrum bands through massive MIMO and beamforming and beam-tracking, some may deploy these spectrum assets towards fixed wireless access application in a similar manner as Verizon. Why not put a good spectrum asset to use when the underlying network infrastructure, in terms of small cells, sites, backhaul, etc. can be extended to the mobile application when a handset ecosystem has had a chance to catch up.

The use of this millimeter wave band is not exclusively tied to 3GPP however. Starry has created a proprietary fixed wireless system based on an 802.11-based chipset solution from Marvell using the 37 GHz millimeter wave band. The company's selection of the 37 GHz band is strategic, in our opinion, as FCC is expected to license over 2 GHz of this spectrum sometime in late 2018 or 2019.

60 GHz Unlicensed

The 60 GHz unlicensed band provides a tremendous amount of spectrum bandwidth. With a high oxygen attenuation in the 60 GHz band, the use of this band for fixed wireless is confined to short-reach distances, less than 300 meters. While this band has been used in point-to-point (PtP) context for many years, many vendors are developing point-to-multipoint (PtMP) systems to take advantage of the large swath of spectrum for high-speed broadband access in urban and suburban settings. Many vendors including Nokia, Siklu, Intracom, and many others provide PtMP solutions operating in the 60 GHz band. Because of high attenuation and shorter reach, the 60 GHz PtMP solutions will require outdoor antenna deployment and high-gain beamforming capability to enable fast installation and activation.

5. ECONOMICS OF FIXED WIRELESS ACCESS

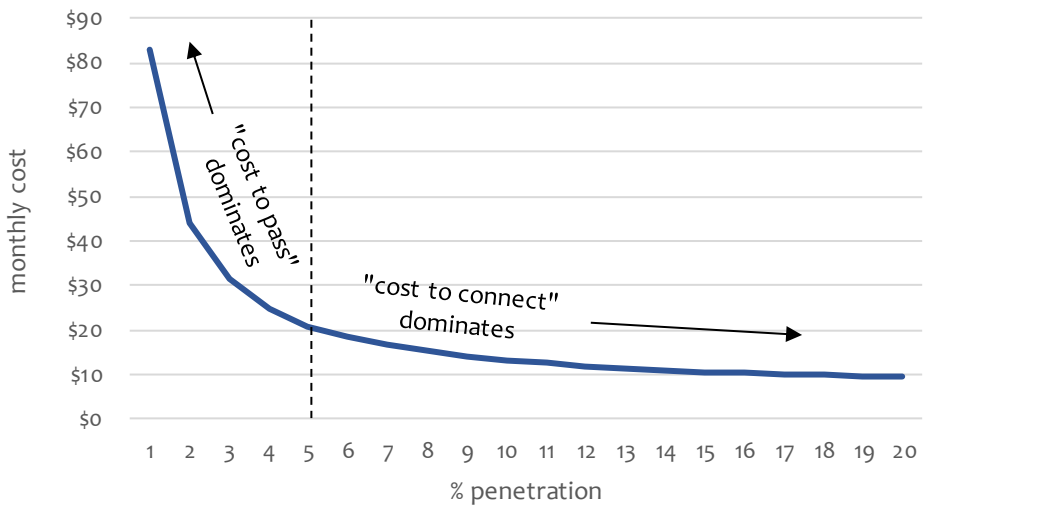
Fixed wireless economics, driven by technology advancements and spectrum availability, continues to advance, offering higher-speed broadband capabilities at lower costs. Both 802.11-based and 3GPP-based (LTE and 5G) fixed wireless technologies continue to lower the "cost per GB" unit economics -- opening new market opportunities and solutions to a wide array of service providers ranging from enterprising WISPs and OTT competitive carriers to large incumbent operators. Moreover, new spectrum choices in both unlicensed and licensed bands--ranging from sub-1 GHz to the millimeter wave bands--are bringing a wide array of fixed wireless options to both rural and urban markets.

Unit Economics of "Cost to Pass" and "Cost to Connect"

In fixed wireless, numerous levers control the overall network cost. Such factors as spectrum cost, cell range, market density, base station, and CPE costs, along with other operational expenses like site and backhaul costs, all impact the overall network cost. The fixed wireless unit economics, like other broadband technologies, is ultimately driven by the "cost to pass" and the "cost to connect" a subscriber. In fixed wireless, the "cost to pass" is driven by the base station, spectrum cost (in case of licensed band use), site lease, backhaul, and power. Meanwhile, the "cost to connect" is primarily driven by customer premise equipment (CPE) or subscriber radio unit, and a "truck roll" for professional installation of CPE, radio tuning, and service activation.

A unit cost curve of a fixed wireless system, on a monthly basis, is shown below.[9] At lower market penetration, the overall network cost curve is dominated by the "cost to pass" components since there are not enough subscribers on the network to "spread" the initial capital expenditure of base station and associated site costs. As the market penetration increases, i.e., as more subscribers are added to the network, the overall network cost is primarily driven by the "cost to connect" components, i.e., CPE and installation costs.

[9] The illustrated network cost curve depicts a LTE fixed wireless system with a $40K LTE macro base station with a cell range of 1.5 miles in a suburban environment of ~1000 homes per square mile. The model assumes $120 LTE fixed CPE.



Source: Mobile Experts

Figure 19. Cost optimization against expected market penetration

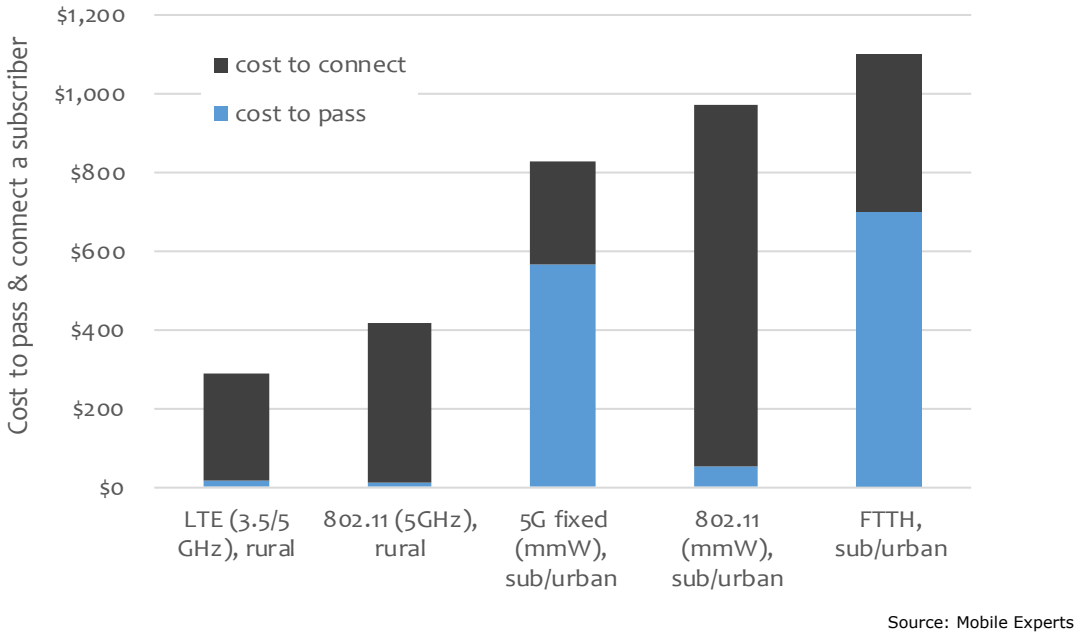
What this implies is that if an operator believes that it won't achieve high market penetration (for competitive or other reasons), then it would likely focus on a fixed wireless system that offers lowest possible "cost to pass." In other words, the operator would try to lower base station and other site costs. On the other hand, if the operator believes that it can achieve high market penetration, it would likely focus on the "cost to connect" components, i.e., CPE and installation/activation costs. Ultimately, a service provider is constantly optimizing network cost against market demand to make sure the service can be delivered at a profit.

Fixed Wireless Cost Advantage over Wireline

One of the key aspects of fixed wireless economics is that it provides a cost advantage over a typical wireline technology like FTTH. More importantly, it provides quick time to market advantage. Standing up a fixed wireless base station site to cover a wide geographic coverage is certainly a lot quicker than trenching fiber or coaxial cable through neighborhoods.

The figure below illustrates the cost advantage of fixed wireless over a typical wireline technology such as fiber. Specifically, the figure compares the total cost to connect a subscriber through a couple of fixed wireless variants vs. fiber to the home (FTTH). The first two bars in the below figure represents the total cost to pass and connect a subscriber through LTE and 802.11-based fixed wireless solutions in a

typical rural environment[10] while the next two bars represent 5G fixed and 802.11-based millimeter wave system in suburban/urban setting[11]. Lastly, the right-most bar shows an FTTH cost for a typical suburban/urban environment in the USA. It should be noted that FTTH cost is highly dependent on market density and region. In sparsely populated locations or high-cost regions, the FTTH cost can be almost $3000 per line.



Source: Mobile Experts

Figure 20. Cost to pass and connect a subscriber via FWA vs. FTTH

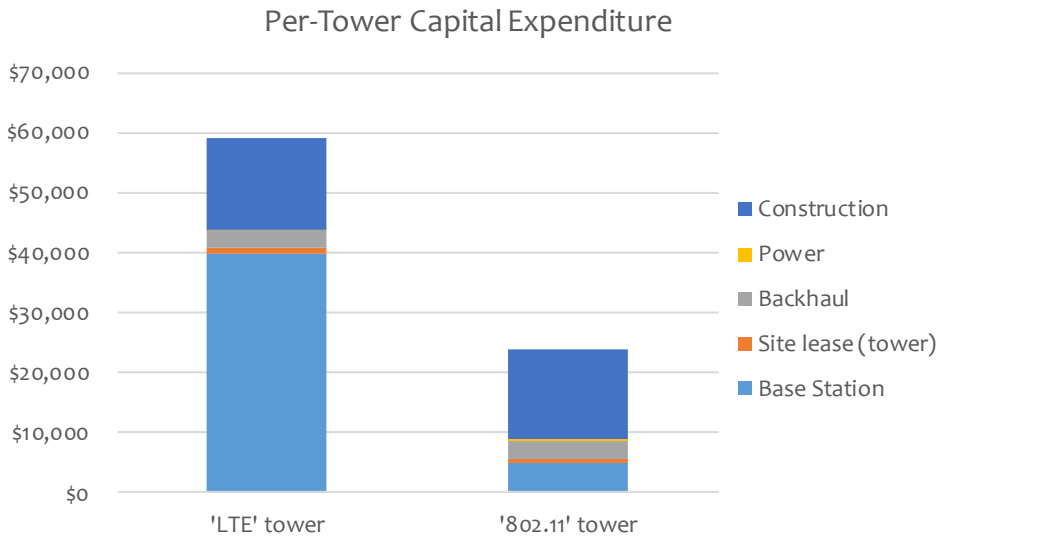
Economic Tradeoff of 3GPP-based vs. 802.11-based FWA Solutions

One of the trends in the rural WISP market is the increasing use of LTE fixed solutions. Despite a general notion that LTE systems require licensed spectrum bands, several companies offer LTE fixed wireless use in the unlicensed bands, such as the 5 GHz band, for those who do not have access to licensed spectrum. While not officially MulteFire certified per se, solutions from several Chinese vendors including ZTE and Baicells, offer LTE radio gear designed for the unlicensed 5GHz band.

[10] A fixed wireless cell distance can range up to 3-4 miles in rural deployments to maximize the number of locations in a given coverage area. Our model assumes a rural market density as ~500 homes per square mile.

[11] We modeled the 5G fixed wireless costs based on our current understanding about Verizon's upcoming 5G home broadband service. We believe the average cell distance would be 300 meters, with conservative cost estimates for site lease and backhaul, and a CPE cost of ~$200.

Upfront capital expenditure costs of installing an "LTE" base station tower vs. 802.11-based "Wi-Fi" tower can be significant for enterprising WISPs with limited capital expenditure budget. Mobile Experts estimates that the total upfront capital expenditure, including one-time construction costs, to build out a rural "LTE" tower can cost about $60,000 today. In contrast, this cost for a "Wi-Fi" base station tower is about $24,000 as shown below.



Source: Mobile Experts

Figure 21. Upfront cost to build out an "LTE" vs. (802.11-based) "Wi-Fi" tower

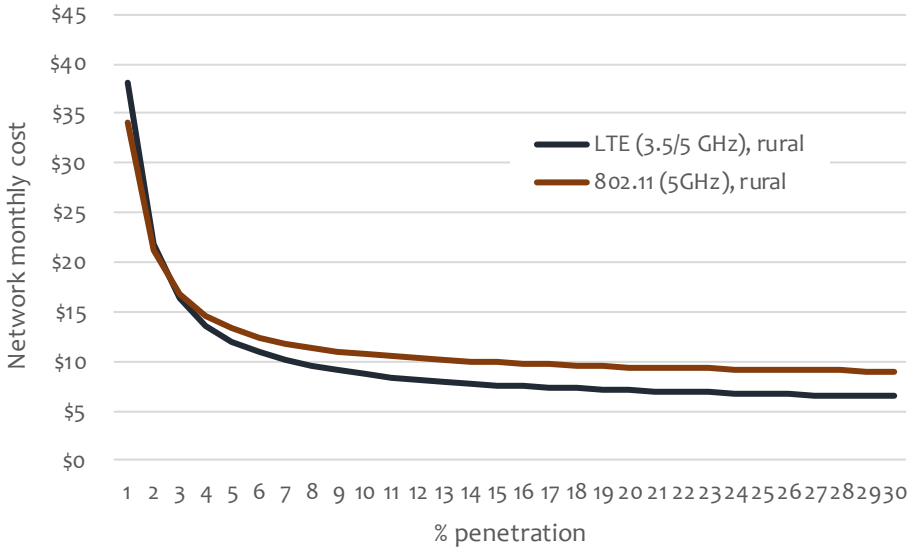
The meaningful cost difference in opting for a 3GPP-based "LTE" tower vs. an 802.11-based "Wi-Fi" tower stems from the fact that a typical LTE macro base station can cost almost ten times higher than an 802.11-based fixed wireless access base station such as Cambium PMP 450. Besides the base station and construction costs, other major items include backhaul and site lease. Our cost model assumes a blended cost of fiber (a very small portion) and a pair of point-to-point radios for wireless backhaul (~$3000) commonly used in rural deployments. Also, our model assumes a blended cost of traditional and non-traditional "tower" site lease cost of ~$750.[12] So, the question is: why would an operator seek LTE fixed wireless solution over the 802.11-based solution, when the upfront capital investment for an LTE system can be meaningfully higher than an 802.11-based fixed wireless system?

Despite the higher upfront capital outlay, some operators are choosing 3GPP-based LTE fixed wireless solution for strategic and economic reasons. Strategically, the

[12] A blended rural tower site lease cost is calculated as 1/3 of traditional cell tower cost of $1200 plus 2/3 of non-traditional "tower" (e.g., water tower, roof top, etc.) cost of $500. In some instances, the non-traditional tower cost can be much lower depending on local market demand for high-speed broadband services and a willingness to forgo or subsidize the site lease cost to enable such services.

3GPP-based LTE radio gear is perceived to provide performance and scale advantages over 802.11-based proprietary solutions. Some operators state that LTE gear typically has a longer lifetime on towers, thus provide a better network investment over a longer time horizon than some 802.11-based gears. Moreover, these operators point out that a larger LTE ecosystem provides a robust technology roadmap and a strategic assurance that there will be multiple vendors who can supply the necessary network infrastructure.

Besides the strategic reasons for LTE fixed gear, some operators are driven by economics in choosing LTE over 802.11-based proprietary solutions. The figure below illustrates the overall network costs of an LTE vs. 802.11-based fixed wireless system in a rural setting.[13] It shows that while the 802.11-based system is cheaper at very low market penetration rates (below 3% in the figure below), the LTE system is cheaper in most cases. This is because LTE-based CPEs are cheaper than 802.11-based proprietary systems. While there are less expensive 802.11-based CPEs in the market, like Ubiquiti for example, some larger operators see a strategic value in standard-based LTE solutions that presumably offer interoperable CPEs from multiple vendors, not tied down to vendor-specific CPE's associated with base station gear.



Source: Mobile Experts

Figure 22. 802.11-based vs. LTE Fixed network costs in rural deployment

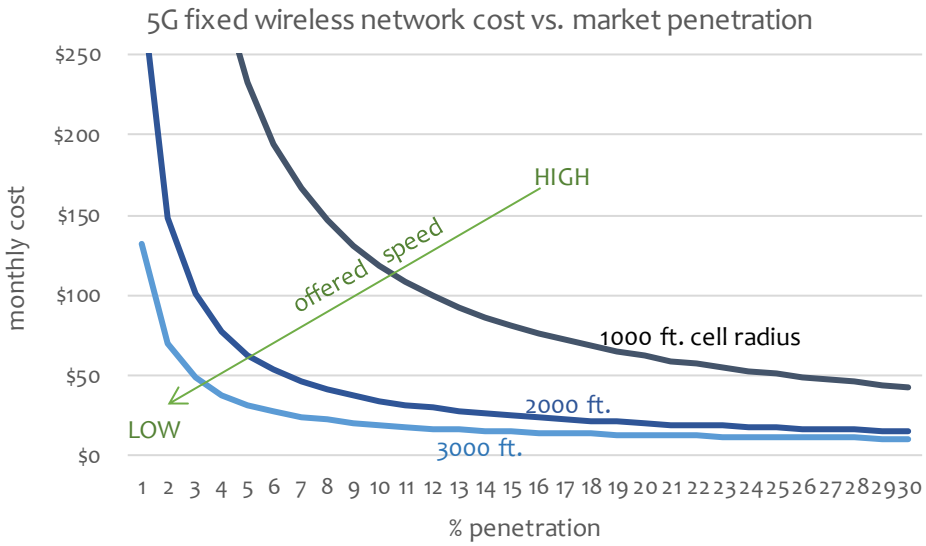
The choice between LTE vs. 802.11-based fixed wireless access system essentially comes down to a tradeoff between higher upfront CapEx cost vs. less expensive CPEs. For larger operators who have lots of subscribers on their networks already, or

[13] The "rural" cost model assumes a fixed wireless base station with a 3-4 mile cell range covering a market density of ~500 homes per square mile. For LTE, $40K macro base station and $120 CPE costs are assumed. For 802.11-based system, we assume $4900 for a 4-sector base station and $255 for CPE.

expect to achieve high market penetration, may see the higher upfront capital expenditure as a necessary investment towards attaining lower network cost structure (i.e., cheaper LTE CPEs). For enterprising service providers with limited "start-up" capital, 802.11-based solutions offer lower-cost base station gears to start, but typically have higher-cost CPEs as compared to LTE ecosystem.

Fixed Wireless Economics of Distance vs. Speed

One of the fundamental tradeoffs in broadband economics is the tradeoff between distance vs. speed. As the distance increases, speed decreases. In fixed wireless access, a cell's range is an artificial limitation of what a particular technology can deliver, in terms of network capacity, against offered or advertised speed to subscribers. It is a balancing act of maximizing distance to cover as many potential subscribers as possible while providing high enough "Mbps" speed to subscribers to make the broadband service compelling.



Source: Mobile Experts

Figure 23. Fixed wireless economics of speed vs. reach

As illustrated in the 5G fixed wireless network cost curves above[14], there is an economic tradeoff between offering higher speed at a short distance vs. presumably slower speed offer at a longer distance. Assuming a "1 Gbps" speed offer can be made at the 1000 ft. cell radius case for $100 with a 50% margin expectation[15], the

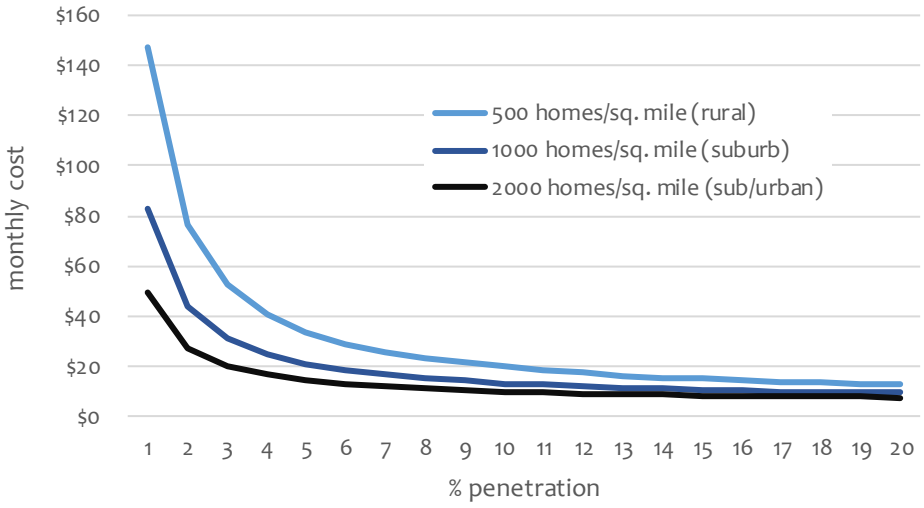
[14] The "5G fixed" cost model assumes the market density of 500 homes per square km (or ~1300 homes per square mile).

[15] Based on Verizon's preliminary "5G home broadband" pre-commerical results showing 1 Gbps median speed at 1000 ft. radius, and some gigabit service offering at above $100 in the marketplace, we believe that this is a reasonable offer in the marketplace.

network cost model implies that an operator needs to achieve 25% market penetration. Similarly, assuming an operator can deliver "200 Mbps" speed at 2000 ft. cell radius for $70 with a 50% margin expectation, then the model implies that the operator needs to achieve about 10% market penetration. Depending on market demand, we would expect an operator to optimize this "cell distance-speed" tradeoff against network cost structure to deliver fixed wireless service at a profit.

Favorable Economics of Dense Markets

Fixed wireless access, or more broadly broadband, economics is heavily dependent on market density. Deploying a broadband network in the heavily dense market provides better economics since the "cost to pass" goes down as more homes and business locations can be addressed with fixed network deployment. As an illustration, the below figure delineates a total network cost, including the "cost to pass" and the "cost to connect," across three different scenarios of market density.



Source: Mobile Experts

Figure 24. LTE fixed wireless network cost vs. market density

The fixed wireless access ROI is more favorable for a denser market environment (note the lower network cost curve for the '2000 homes per square mile' sub/urban case vs. the '500 homes per square mile' rural case). Assuming a cost target of $20 (to have enough margin for a $50 offer to make the business case profitable), the figure shows that the fixed wireless service can reach breakeven at around 10-11% market penetration for the rural case (~500 homes per square mile). In other words, a service provider needs to sign up 50-55 subscribers within the coverage area to achieve profitability! For the sub/urban setting, this "breakeven" market penetration is even lower -- just 4%! While this seemingly low penetration rate seems easy to reach, the 4% market penetration translates to 80 subscribers. In a competitive

market with strong broadband alternatives like cable and fiber from incumbent players, even signing up 80 subscribers may not such an easy feat.

Fixed wireless economics favors deploying in heavily dense markets, as the network cost curve is lower. However, heavily penetrated cable and fiber footprints in dense urban and older suburban markets, and the market competition posed from incumbent players make fixed wireless deployment in denser suburban and urban markets non-straightforward. While fixed wireless access provides an economical means to provide "tens of Mbps" broadband services in rural and underserved markets, "hundreds of Mbps" and "gigabit" fixed wireless service opportunity in urban settings requires a careful assessment of speed offering, demand, and competitive response from incumbent players in the region.

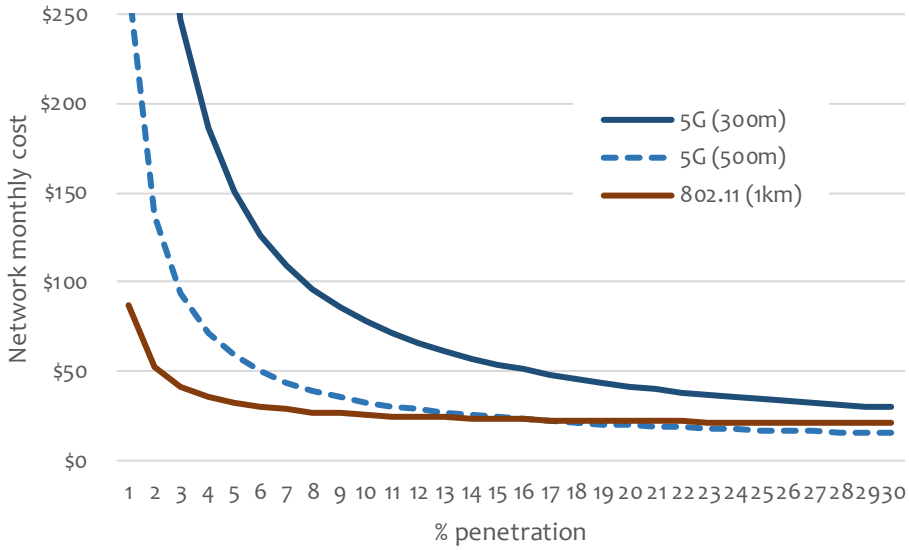
Cost Comparison of 802.11-based vs. LTE vs. 5G Fixed

To evaluate comparative economics of 802.11-based vs. 3GPP-based fixed wireless systems, it is important to make a 'like-for-like' comparison. Speed offer, cell range, market density, and other factors all influence the network cost structure depending on what an operator is trying to optimize. For example, an operator may look to maximize coverage over speed offering for a given market density while another may look to provide high-speed offer over relatively shorter cell distance. To make a fair comparison, we have modeled two use cases: 1) 802.11 vs. LTE in a rural market; and, 2) 802.11 vs. 5G using millimeter wave in an urban market.

The 802.11 vs. LTE fixed wireless network costs for a rural market scenario is shown in Figure 20. Here, we have modeled an equivalent cell distance of 5 km (3-4 miles) for both 802.11-based and LTE base station for a market density of 200 homes per square km (500 homes per square mile). As shown, the two technologies share similar cost profile with the 802.11-based system having better economics at lower market penetration while LTE fixed system providing slightly better economics (~$2 lower monthly cost) over the 802.11-based system. The lower LTE cost structure stems from the fact that LTE CPEs are cheaper than proprietary 802.11-based CPEs, which are vendor-specific. Meanwhile, the standard-based LTE CPEs can be presumably sourced from multiple vendors, thus providing scale advantages and lower cost.

The 802.11-based vs. 5G fixed wireless network costs for an urban setting (2000 homes per square mile) is shown below. Here, we have modeled our 5G fixed case based on our understanding of Verizon's "5G home broadband" service. Meanwhile, we have modeled our 802.11-based (millimeter wave) system based on our understanding of the Starry system in Boston. Since the two systems are optimized for different goals, we have also modeled the "5G (500m)" case to showcase a 5G fixed system assuming that Verizon's 5G fixed service is extended to a 500m cell radius (vs. 300m case for Verizon's baseline case) for "200 Mbps" speed offer as is

the case with the Starry system. While the current "5G" fixed wireless systems from both 802.11-based and 3GPP-based systems offer similar network cost structures, we believe that 5G fixed can drive its cost structure further down as the 5G mobile ecosystem scales up (i.e., as the high-volume smartphone ecosystem adopt millimeter wave band support). We expect this to happen around 2021-2022.



Source: Mobile Experts

Figure 25. 802.11-based vs. 5G Fixed network costs in urban deployment

Economic Optimization – Rural vs. Urban

Based on the economics of fixed wireless and observed market activities, we can draw a few conclusions:

1. A start-up fixed wireless operator may choose to optimize for the "cost to pass" (i.e., look for the lower base station, spectrum, and site costs) before it can gain scale (i.e., higher market penetration);

2. This behavior is commonplace, especially in rural markets where operators are primarily focusing on coverage using unlicensed 802.11-based solutions. Opting for unlicensed spectrum is an obvious one – it's free and readily available, and interference risk from using unlicensed spectrum is low in sparsely populated rural markets;

3. A large-scale or an incumbent fixed wireless operator is likely to be more concerned with the "cost to connect" (i.e., CPE cost). In this case, lowering the CPE cost is likely more important than the initial infrastructure cost. This economic consideration is driving some larger WISPs to transition to LTE fixed

systems to take advantage of lower-cost CPEs. Moreover, they like the 'safety net' of longer-term 3GPP technology roadmap with multiple vendors behind the standards-based ecosystem;

4. Fixed wireless is a natural fit in underserved rural markets where the competition is relatively benign, and there is a pent-up demand for high-speed broadband service; and,

5. Fixed wireless for the urban market will require higher speed offerings than the ones typically found in rural/suburban markets. The wider spectrum bandwidth available in the millimeter wave bands is a natural fit, but the economics of extending cell range needs a careful tradeoff consideration against higher complexity, hence cost, of a CPE. Starry's high-cost CPE system appears to be focusing on extending cell range to maximize the market opportunity of MDUs first.

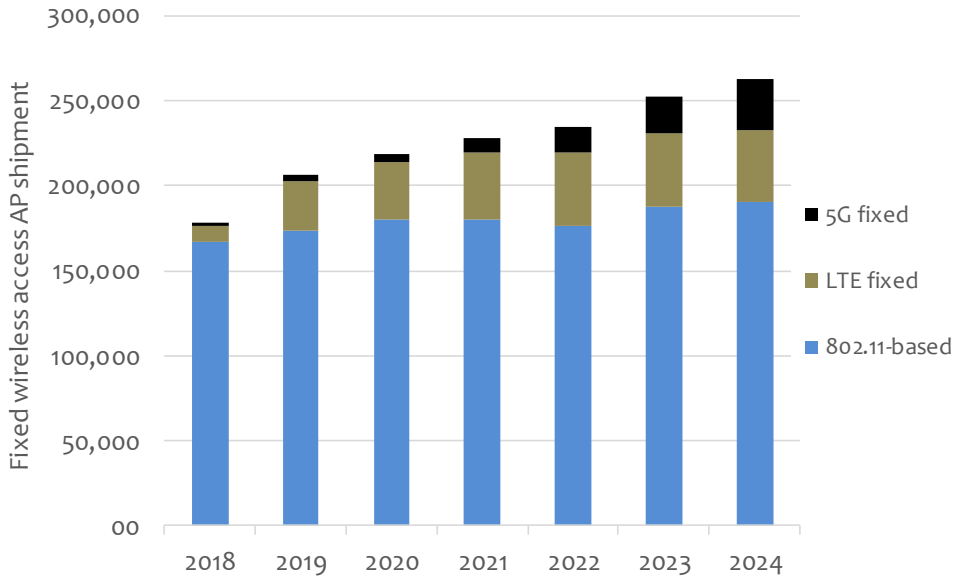
6. Meanwhile, Verizon's 5G fixed architecture uses the small cell model (~300m cell range) which appears to be optimized for throughput performance (~1 Gbps) rather than coverage. While the smaller cell deployment model is more expensive to build out, we believe Verizon's motivation is fundamentally different than a startup like Starry. We believe Verizon's primary goal is to eventually transition their 5G fixed wireless infrastructure to mobile use. Verizon's 5G investment is mobile-first, while a startup like Starry is fixed-first.

6. FIXED WIRELESS ACCESS EQUIPMENT SHIPMENTS

The growing fixed wireless access (FWA) equipment market can be segmented into 802.11-based proprietary solutions and 3GPP-based LTE and 5G solutions. The 802.11-based fixed wireless solutions from historical vendors in the space such as Cambium, Ubiquiti, and others provide a range of point-to-point (PtP) and point-to-multipoint (PtMP) radio products for wireless backhaul and access systems. While these 802.11-based solutions remain a bedrock of many fixed wireless access systems today, 3GPP-based LTE and 5G solutions for the fixed wireless access use are expected to grow as Tier-1 operators target rural and some dense urban markets with the standards-based approach.

Fixed Wireless Access Equipment Forecast by Technology

While today's fixed wireless access market is dominated by unlicensed 802.11-based proprietary systems, Mobile Experts forecasts a growing adoption of standards-based LTE systems for this market. We believe this adoption will primarily come from mobile/telco/cable and larger WISP operators. These major telecom players will be driven by government programs (e.g., CAF II, Rural Digital Opportunity Fund in the USA) and internal motivation to extend their primary wireline footprints with the alternative broadband network with standards-based technology that offer long-term technology roadmap. Also, larger WISPs, who are drawn to the standards-based LTE ecosystem that generally offer lower-cost CPEs, will increasingly adopt LTE as they go through infrastructure refresh cycles.



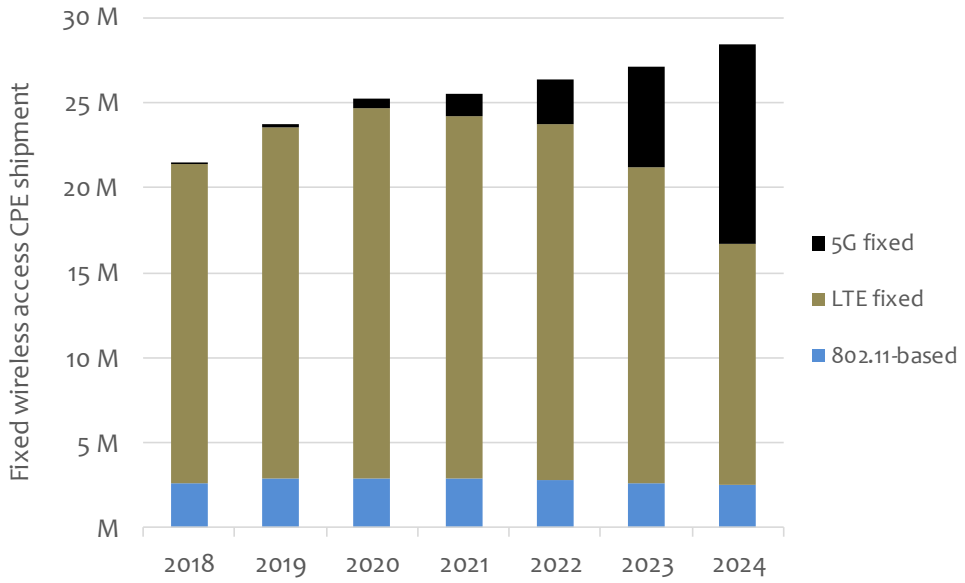
Notes: 1) "LTE fixed" AP shipments reflect new base stations specifically dedicated for the fixed wireless application.
2) Existing mobile LTE base stations shared across both mobile, and fixed broadband access are not counted.

Source: Mobile Experts

Chart 2: Fixed wireless access AP shipment by technology, 2018-2024

Mobile Experts forecasts the 802.11-based proprietary AP shipments to remain largely flat during the forecast period while the LTE and 5G base station AP's dedicated for fixed wireless application grow from about 13,000 base station AP's to over 70,000 in 2024. It should be carefully noted that the LTE and 5G base station AP shipments only reflect "dedicated" base station AP's for fixed wireless access. We believe many larger mobile/telco operators leverage their existing LTE, and future 5G, infrastructure on a shared basis to serve both mobile and fixed broadband users. If we were to count the shared LTE and 5G base stations in the mix, the total AP shipment would be much higher.

Our forecast assumes that many of integrated mobile/telco operators will adopt LTE fixed wireless access solutions to leverage their existing LTE core infrastructure. If they decide to separate mobile vs. fixed broadband services on separate infrastructures, then our forecast can change quite significantly. For 5G fixed, we currently expect modest growth in AP unit shipments as we believe 5G fixed market opportunity is somewhat limited by heavy penetration of competing wireline FTTH and cable solutions in dense markets. In developing regions, "gigabit" market opportunity is mostly limited to the enterprise market, which is largely addressed through proprietary point-to-point solutions.



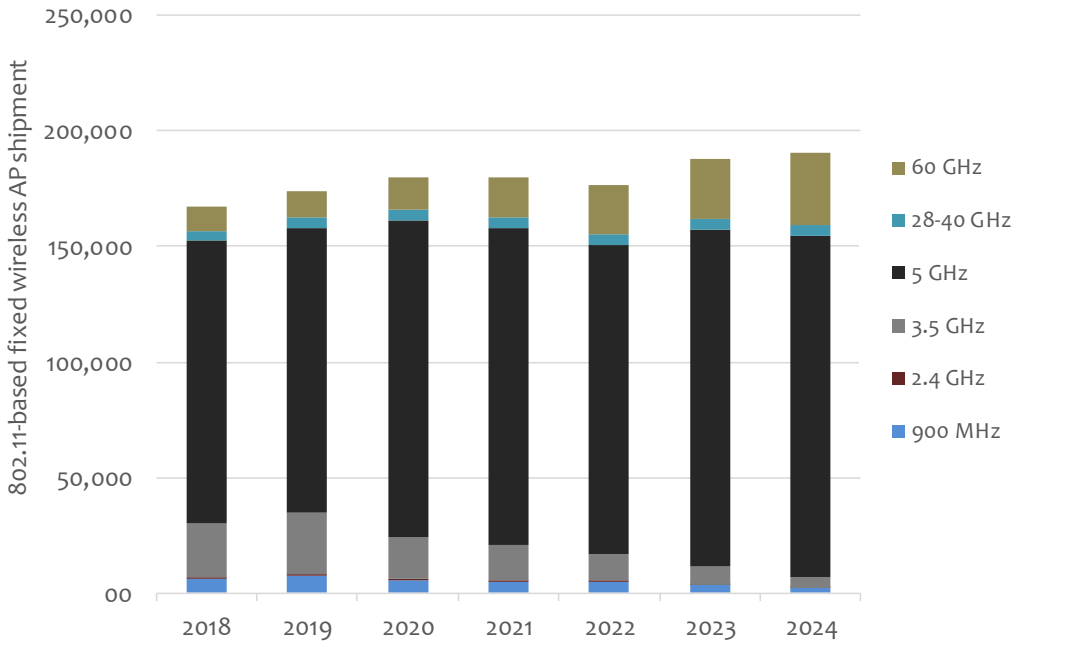
Source: Mobile Experts

Chart 3: Fixed wireless access CPE shipment by technology, 2018-2024

The fixed wireless subscriber CPE shipments are forecasted to grow at 5% CAGR during the forecast period. Most of the growth is expected to come from the LTE and 5G CPE shipments while the 802.11-based proprietary CPE unit shipment is expected to remain flat, hovering around 2.5 - 3M units annually. The LTE fixed CPE shipment is expected to grow near-term rising to just under 22M before declining to about 14M in 2024 as the 5G fixed CPE shipment rises quickly to over 11M units in 2024.

802.11-based Fixed Wireless Access Equipment Forecast

The 802.11-based fixed wireless base station access points (APs) mostly operate in unlicensed bands. (to mostly target WISPs who don't have licensed spectrum). With relative advantages of large chunks of channel bandwidth, decent RF propagation, and less prone for interference in sparsely populated rural target markets, the 5GHz band, more specifically the 5.4 and 5.8 GHz bands, are popular choices for WISPs. While we expect some 900 MHz, 2.4 GHz, and 3.65 GHz base station APs based on proprietary technologies to ship during our forecast period, we expect the number of unit shipments to diminish over time as most of those units will be for replacements rather than new builds.



Source: Mobile Experts

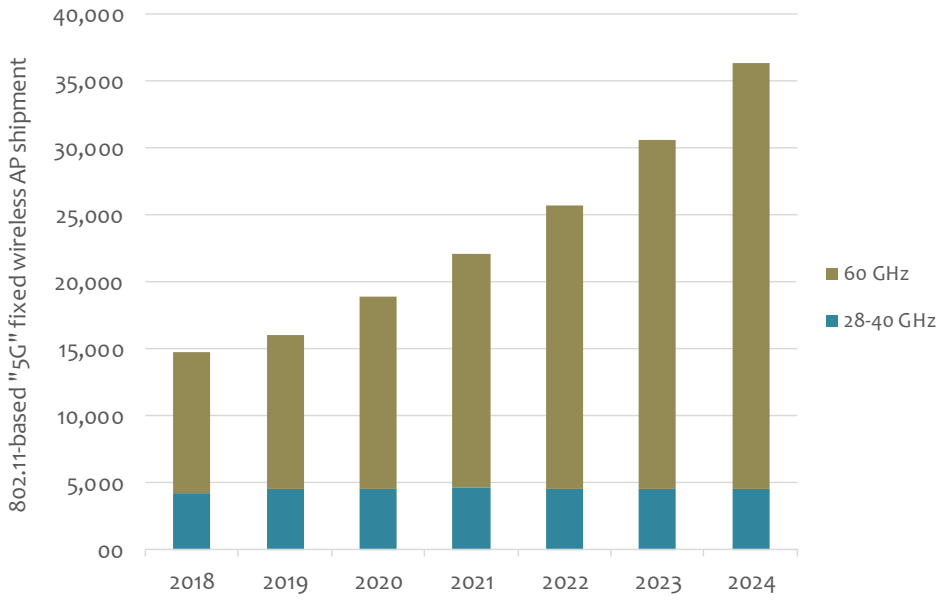
Chart 4: 802.11-based fixed wireless access AP shipment by freq. band, 2018-2024

The 5GHz units will dominate the 802.11-based AP shipments as that particular band affords significant channel bandwidth compared to other bands. For example, the current Part 90 radios operating in the 3.65 GHz band utilizes 50 MHz of channel bandwidth, and some of those are cluttered with competing radios.

Meanwhile, we expect the 60 GHz PtP and PtMP radios for fixed wireless access to grow modestly as the Terragraph 60 GHz PtMP program matures over time. We expect many of these 60 GHz radios to be used for short-distance backhaul in "micro hub" architecture. The actual fixed wireless access to subscriber homes and businesses will require significantly lower CPE cost in $150 range in our estimate rather than several hundred dollar units today. While there is some momentum behind Terragraph from both large and small vendors including Nokia, Cambium, Mikrotik, RADwin, Siklu, and others, the ecosystem will need to scale up in order to achieve the target CPE cost to make the business case viable for operators. We currently estimate this target to be achievable in 2022-2023 at the earliest.

Similarly, the proprietary 28-39 GHz millimeter wave PtMP products will be targeted mostly for enterprise or residential MDU segment to offer "hundreds of Mbps" or "gigabit" service to high-demand markets. Starry is one example of a vendor/operator leveraging this lightly licensed spectrum band with an 802.11-based proprietary fixed wireless solution to these high-value densely populated buildings. Cambridge Broadband Networks Ltd. (CBNL) is another key vendor who has been

active in deploying 802.11-based PtP and PtMP radios in this millimeter wave bands to provide backhaul and enterprise access in many countries including emerging markets in Africa as well as with Tier-2 operators in North America and other developed markets.



Source: Mobile Experts

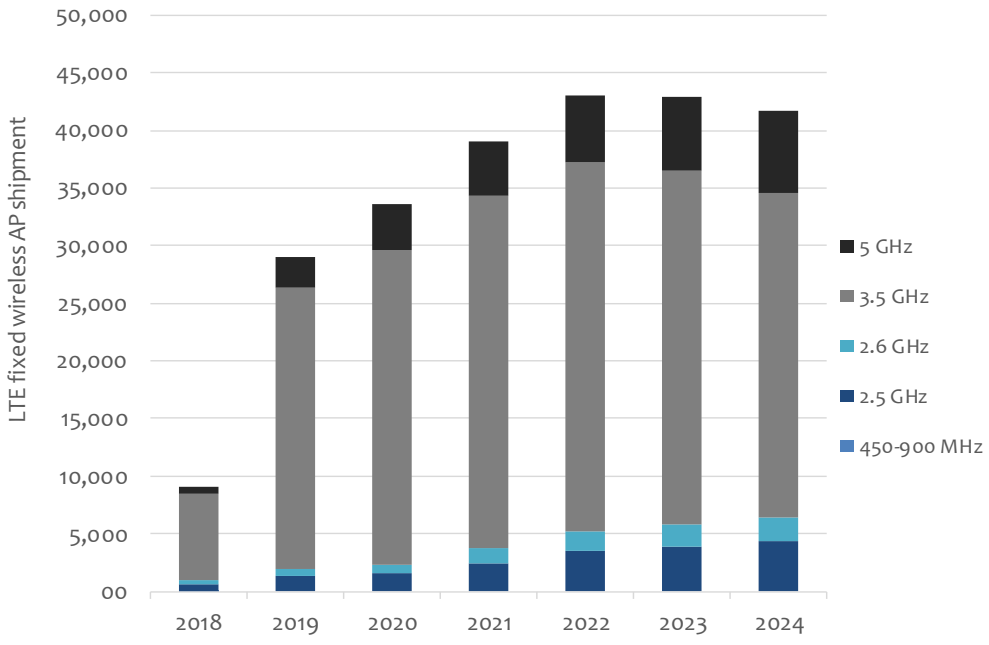
Chart 5: 802.11-based "5G" fixed wireless access AP shipment, 2018-2024

Extracting so-called "5G" fixed wireless technology using the millimeter wave spectrum such as Starry and Terragraph, we can see that this particular segment will provide the growth in the 802.11-based fixed wireless segment. While Starry has announced its plan to expand to almost 20 markets, we believe the number of base station AP's will be moderate in shipment count as the number of markets deployed will depend on the velocity of network deployment and capital at the company's disposal. Mobile Experts believes that the 60GHz Terragraph program will provide economies of scale for the market to grow.

LTE Fixed Equipment Forecast

The "dedicated" LTE fixed wireless base station AP shipment will target new spectrum opportunities in the 3.5 GHz CBRS and 2.5 GHz bands. The CBRS band allocation in the USA will drive major telecom operators and WISPs to tap the expanded spectrum beyond the 3.65 GHz band to potentially tap 150 MHz of spectrum for fixed wireless access. The ramp is expected to start in earnest in late 2019 upon FCC approval post-ICD trials. Also, we expect some shipment of LTE for

5GHz unlicensed band to be deployed among some WISPs as they look to harness network scalability and lower CPE cost structure of the LTE ecosystem.



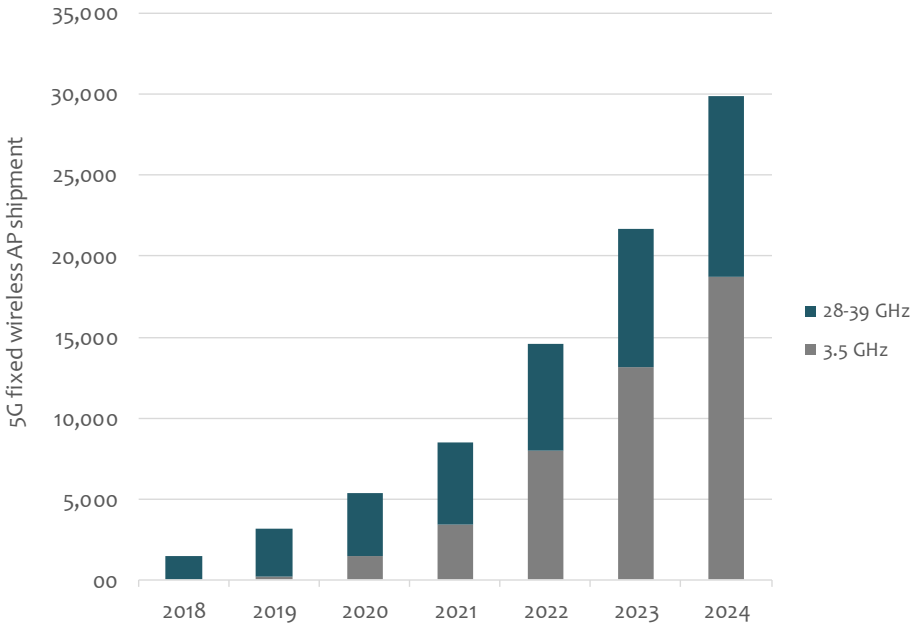
Source: Mobile Experts

Chart 6: LTE fixed wireless access AP shipment by freq. band, 2018-2024

5G Fixed Equipment Forecast

Our 5G fixed wireless AP shipment forecast is primarily driven by Verizon's 5G fixed commercial deployment plan in the near term and 5G network deployment in the 3.5GHz mid-band among major operators in Europe, APAC, and MEA. We expect a few thousand AP shipment in 2018-2019 for Verizon's 5G Home commercial launch in four markets thus far. While Verizon touts 30M household opportunity for its 5G fixed service[16], Mobile Experts believes that Verizon will be selective in markets, and neighborhoods within those markets. The market selection criteria will depend on fiber availability and market profile. While the growth rate is impressive, the actual unit shipments are expected to be modest as we believe Verizon, AT&T, and New T-Mobile will largely target their 5G network capacity for the mobile use case and selectively target high-value enterprise customers or residential MDUs rather than cover individual residential single homes.

[16] Verizon investor presentation on "5G Home Broadband," Nov. 2017



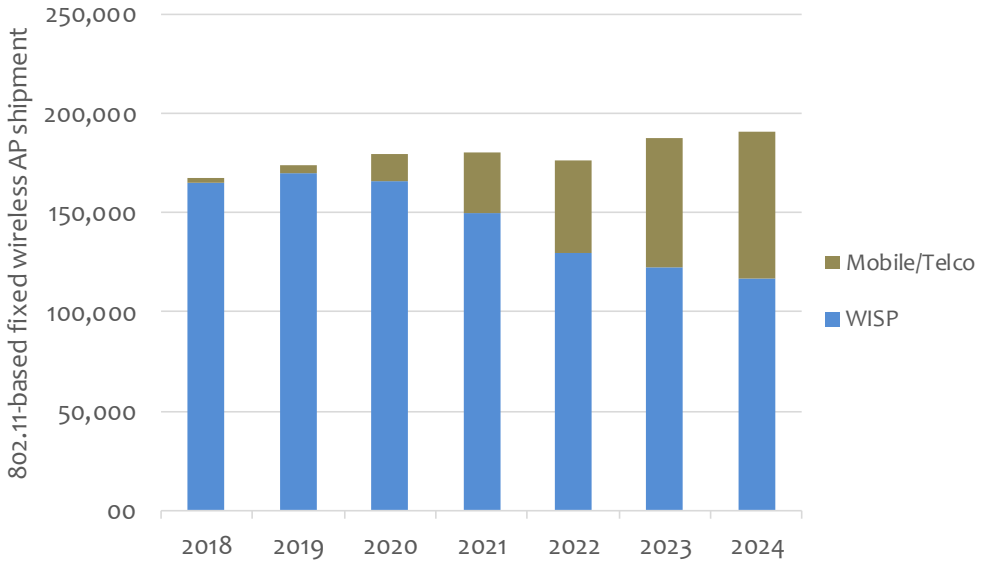
Source: Mobile Experts

Chart 7: 5G fixed wireless access AP shipment by freq. band, 2018-2024

Based on early indications of major operators in Europe, MEA, and APAC leveraging 5G fixed broadband utilizing 3.5GHz mid-band spectrum, we feel much more optimistic about the 5G fixed services coming available on the 3.5 GHz band. Telenor Norway, Elisa in Finland, Telstra in Australia, and almost 20 operators worldwide announcing 5G network services have some component of fixed broadband service offering.

FWA Equipment Forecast by Operator Type

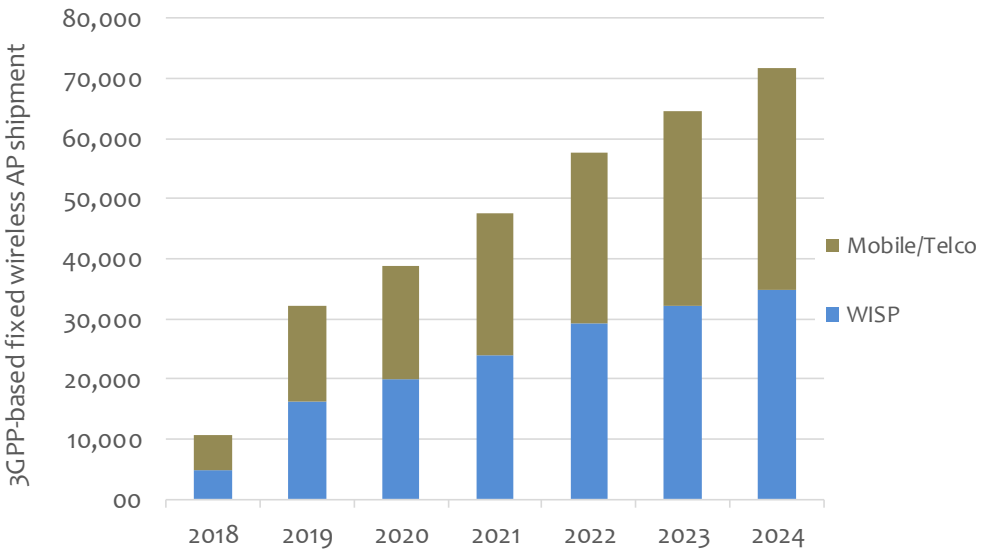
While the dedicated fixed wireless infrastructure is often associated with WISP deployments of 802.11-based radio equipment running on unlicensed spectrum bands, regional Telcos with government funding and commitments will increasingly deploy fixed wireless access infrastructure in the coming years. Depending on the broadband commitments (e.g., 25/3 Mbps or 100/20 Mbps down/uplink speeds) and locations targeted, Telcos and WISPs will leverage both 802.11-based and 3GPP-based gears for their fixed wireless access deployments.



Source: Mobile Experts

Chart 8: 802.11-based fixed wireless access AP shipment by operator type, 2018-2024

The 802.11-based proprietary fixed wireless AP shipment volume will continue to be driven by the WISP operators. The WISP market is highly fragmented with many operators with limited scale in subscriber count. Many of these enterprising WISPs will be drawn to 802.11-based solutions with relatively lower infrastructure cost as compared to 3GPP-based solutions. However, as the market consolidates and larger players' preference for lower economics of LTE CPEs, the unit shipment of 802.11-based infrastructure to WISPs will gradually wane. At the same time, smaller regional Telcos and some competitive carriers like Starry with the smaller-scale fixed wireless launch will adopt 802.11-based proprietary solutions, especially in higher-band millimeter wave solutions with large channel bandwidths.



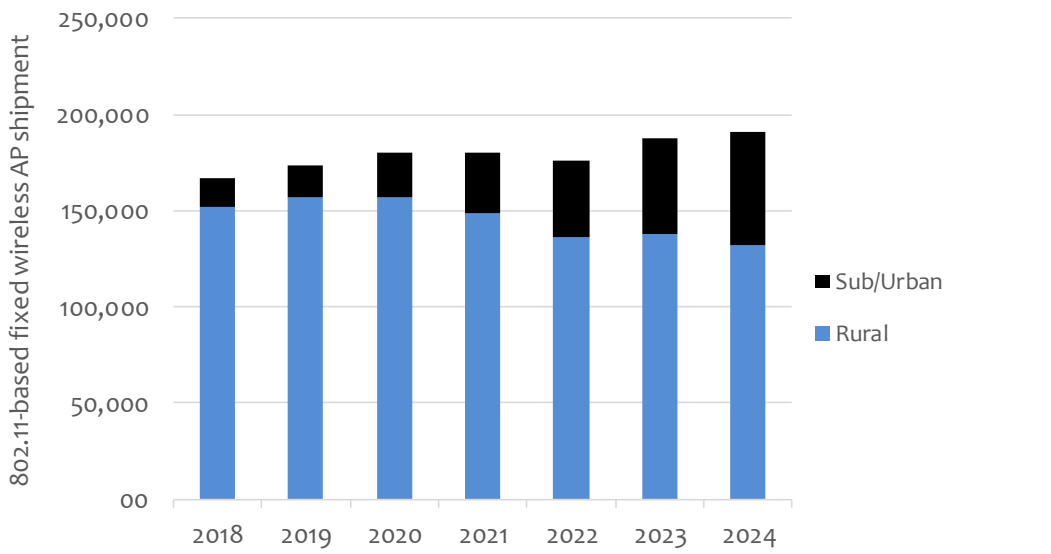
Source: Mobile Experts

Chart 9: 3GPP-based fixed wireless access AP shipment by operator type, 2018-2024

The 3GPP-based LTE and 5G fixed wireless AP shipment volume will be driven by both WISP and mobile/telco operators. The WISP adoption of LTE solutions is driven by spectrum availability in the 2.5 GHz and 3.5 GHz CBRS band as well as the availability of LTE gear that operates in the 5 GHz unlicensed band. Moreover, advancements in the LTE small cell ecosystem has brought price-competitive LTE base station gear to the market to compete against "high-end" 802.11-based proprietary systems such as Cambium's PMP-series products. While the price difference between "high-end" 802.11-based system like Cambium PMP 450 and LTE base station gear remains, the cost difference has come down when compared to a traditional LTE macro base station. Meanwhile, some mobile operators like Verizon and AT&T are opportunistically launching 5G fixed wireless systems in the millimeter wave bands; we expect these to be minimal in the near term. Meanwhile, we see some Tier-2/3 Telcos will leverage LTE fixed wireless equipment to extend their broadband footprints through private investment or government funding like CAF II. The availability of CBRS and CAF II based infrastructure deployment to pick up in the later half of 2019 and ramp-up in 2020.

FWA Equipment Forecast by Market Density

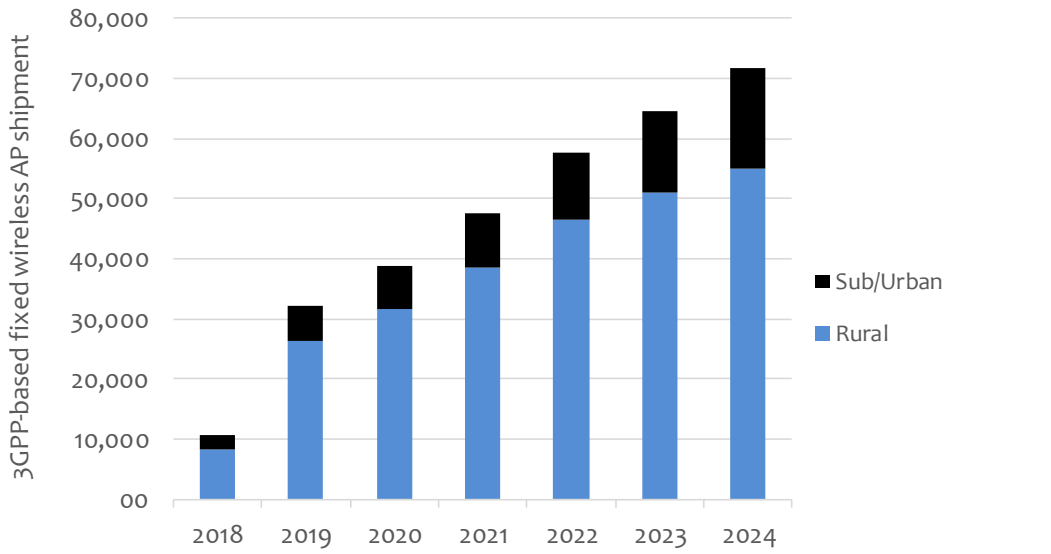
The fixed wireless access market will continue to focus on the core rural locations. However, the "micro hub" architecture, opening up of new spectrum bands, and availability of point-to-multipoint (PtMP) millimeter wave systems will continue to push the fixed wireless deployments towards denser suburban, and in some remote cases urban, markets.



Source: Mobile Experts

Chart 10: 802.11-based FWA AP shipment by market density, 2018-2024

While the 802.11-based fixed wireless access deployments are associated with rural deployments where the unlicensed spectrum use is more tolerable with lower chances of co-channel interference, new gears leveraging MU-MIMO features in 802.11ax and new spectrum bands in both unlicensed (60GHz) and lightly licensed millimeter wave bands (24-40 GHz) to offer solutions that can address suburban and urban deployments. While the 802.11-based base station AP shipments for the core rural deployments will decline slightly, largely due to lower replacements, the 802.11-based AP shipments for the suburban and urban deployments will increase from about 16k units in 2018 to about 60k units in 2024. The overall unit shipments of 802.11-based fixed wireless access AP's will increase slightly as the new "5G" gears leveraging the millimeter wave bands and Tier-2/3 Telco deployments will provide a "tailwind" to the market.



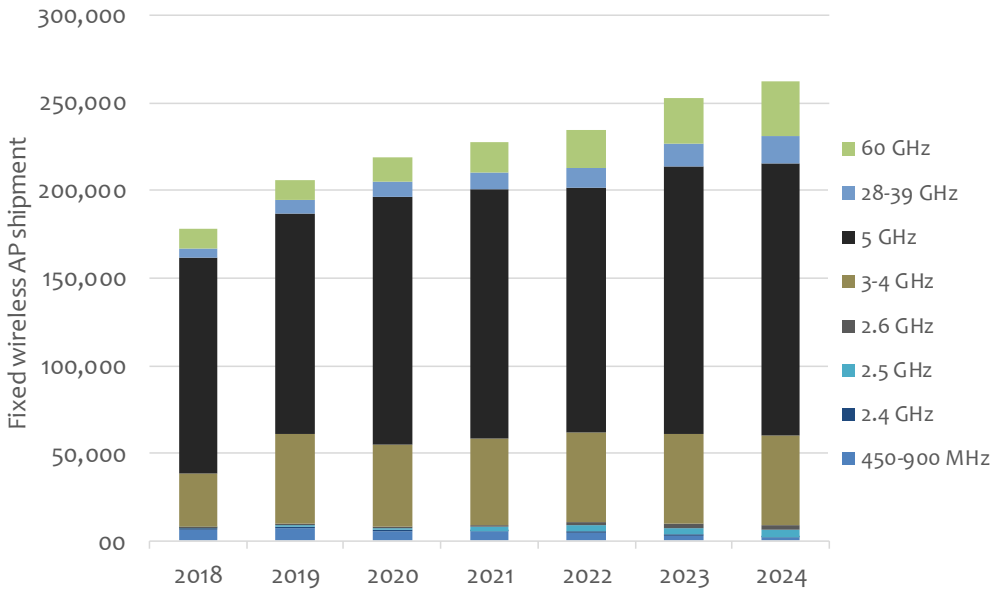
Source: Mobile Experts

Chart 11: 3GPP-based FWA AP shipment by market density, 2018-2024

Mobile Experts expects a similar dynamic in the LTE and 5G fixed wireless space as well. Even though there is a greater opportunity to address suburban and urban fixed broadband opportunities with millimeter wave band, for example, we expect major mobile/telco operators to limit the scope of 5G fixed wireless deployment especially in the developed markets in North America. In Europe, we see a different dynamic. Despite high penetration of fixed broadband penetration, some Tier-1 operators in Europe are targeting 5G fixed wireless to address DSL replacements. Instead of opting for fiber optics, some are choosing to leverage 5G in the 3.5GHz mid-band to target remote villages that are too costly to extend fiber to customer premises. Meanwhile, LTE fixed wireless gears leveraging new spectrum bands such as 3.5 GHz CBRS and 2.5 GHz bands will be popular among regional operators with government funding to extend higher broadband footprint.

FWA Equipment Forecast by Spectrum Bands

Operating frequency bands for fixed wireless access application span across from the 900 MHz to 60 GHz millimeter wave bands. Mobile Experts forecasts a steady growth (6% CAGR) of unit shipments of both 802.11-based and 3GPP base station AP gears.



Source: Mobile Experts

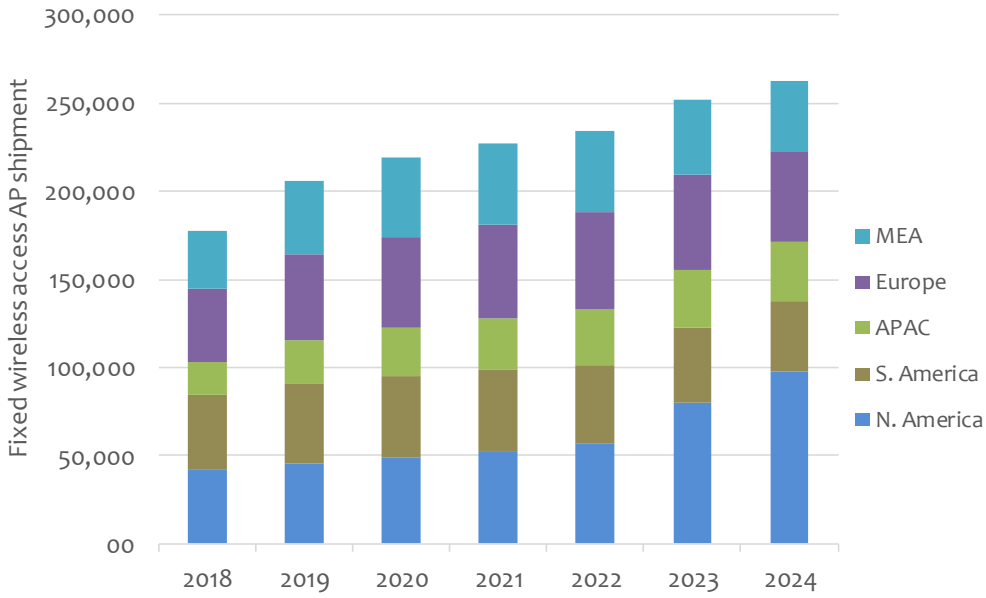
Chart 12: Fixed wireless access AP shipment by spectrum bands, 2018-2024

The unlicensed 5 GHz band is the most popular band for fixed wireless application due to its global scale, a several hundred MHz of spectrum bandwidth, and a broad ecosystem Wi-Fi chipset suppliers. The use of 3-4 GHz and is expected to ramp up as the band gets opened up under CBRS rule in the USA and 5G-designated mid-band in many regions. Meanwhile, the 5G fixed in the millimeter wave bands as well as the 60 GHz deployments will provide faster ramp around 20% CAGR. However, the volume of unit shipments will differ substantially – about 40k-50k units for the millimeter wave and 60 GHz gears as compared to about 200k units for the sub-6GHz base station AP gears in 2024.

For a detailed breakdown of 802.11-based AP shipment by operating frequency, please refer to Chart 4. For LTE-fixed and 5G-fixed AP shipments by operating frequency, please refer to Charts 6 and 7 respectively.

Regional Forecast

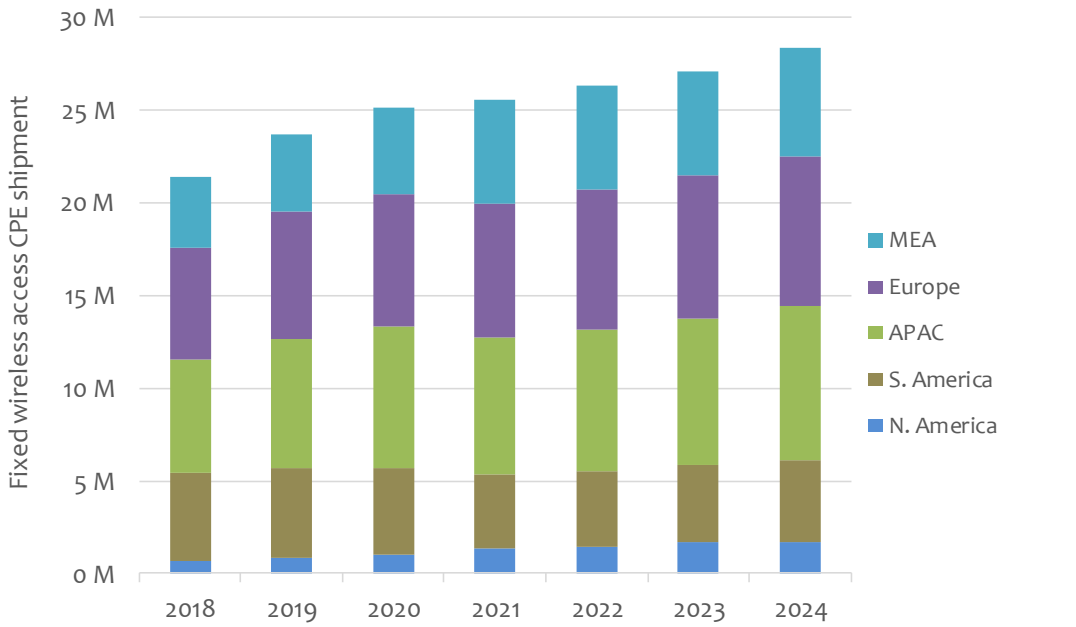
Regional outlook for fixed wireless base station AP and CPE shipments differ widely as the "dedicated" base station AP shipment is largely driven by "unlicensed" 802.11-based AP units concentrated in North America, Europe, and Latin America, while the CPE shipment is largely driven by LTE, and 5G CPEs concentrated in regions outside of North America. While the North American market will increasingly adopt LTE gears, the scale of LTE CPE shipment in North America is much lower than in other regions.



Source: Mobile Experts

Chart 13: Overall fixed wireless access AP shipment by region, 2018-2024

North America represents the largest market for "dedicated" fixed wireless base station AP equipment. With an estimated 2500 WISPs serving underserved broadband markets primarily in rural areas, North America has a business environment and ecosystem of distributor networks that foster this type of enterprising business. Fixed broadband access is a regional business in nature; i.e., one does not need to have a nationwide scale to start, which is the case in the mobile wireless business today. Anyone with entrepreneurial drive and some start-up capital can offer up broadband service after setting up a few base stations on the air. The business can bootstrap from there. Europe and South America are the other two significant markets for fixed wireless as those regions have limited wireline broadband infrastructure. Hence, fixed wireless is a cost-effective way to address the increasing broadband demand. APAC, in contrast, is not a huge market for "dedicated" fixed wireless AP market as major operators typically leverage their fixed broadband and mobile networks. The market is heavily dominated by large telecom players, and many are leveraging their mobile network to add fixed wireless broadband service on top of the mobile broadband offering.



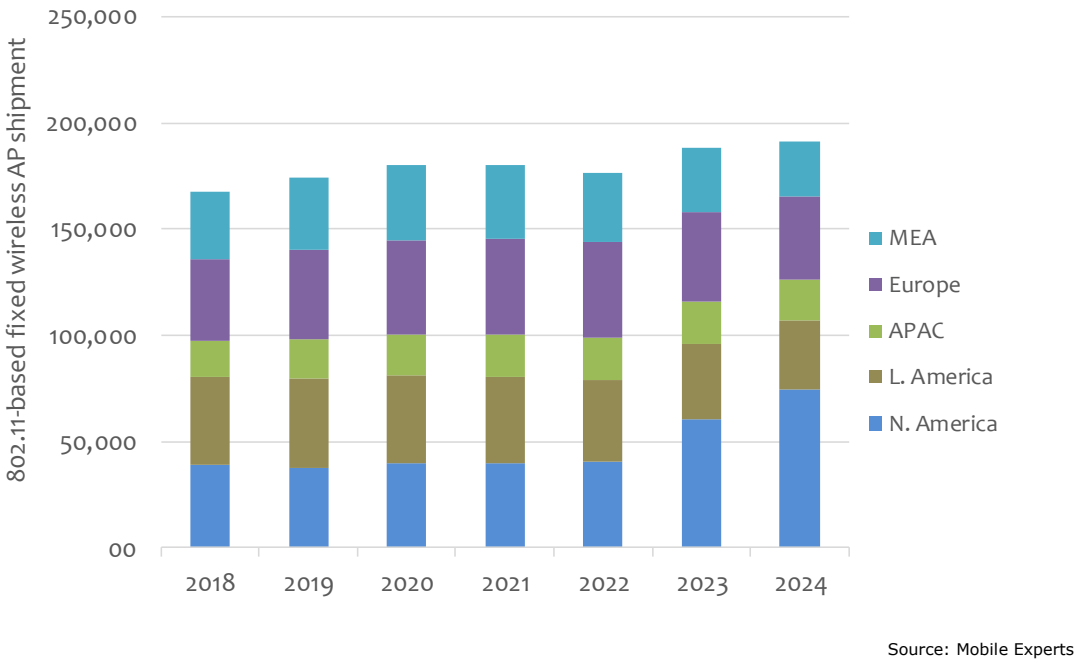
Source: Mobile Experts

Chart 14: Overall fixed wireless access CPE shipment by region, 2018-2024

Regarding CPE shipments, APAC and Europe represent larger markets as the integrated mobile/telco operators are leveraging LTE mobile networks to address the growing broadband need. With about 40 MHz of spectrum, operators can deliver "tens of Mbps" to about 100 Mbps service. While some are using the same carrier channel for mobile and fixed service, some are looking to deploy a dedicated channel carrier to ensure better quality. Due to the huge scale at which these large mobile operators can distribute CPEs, these regions are the key markets for (mostly LTE) CPE shipments. North America, in contrast, is relatively a small market for fixed wireless CPE's as the market is skewed towards "high end" 802.11-based gears with higher-cost CPEs. We generally find a high volume of lower-cost CPE gears in developing regions such as Latin America, Eastern Europe, MEA, and parts of Asia.

802.11-based FWA Equipment Regional Outlook

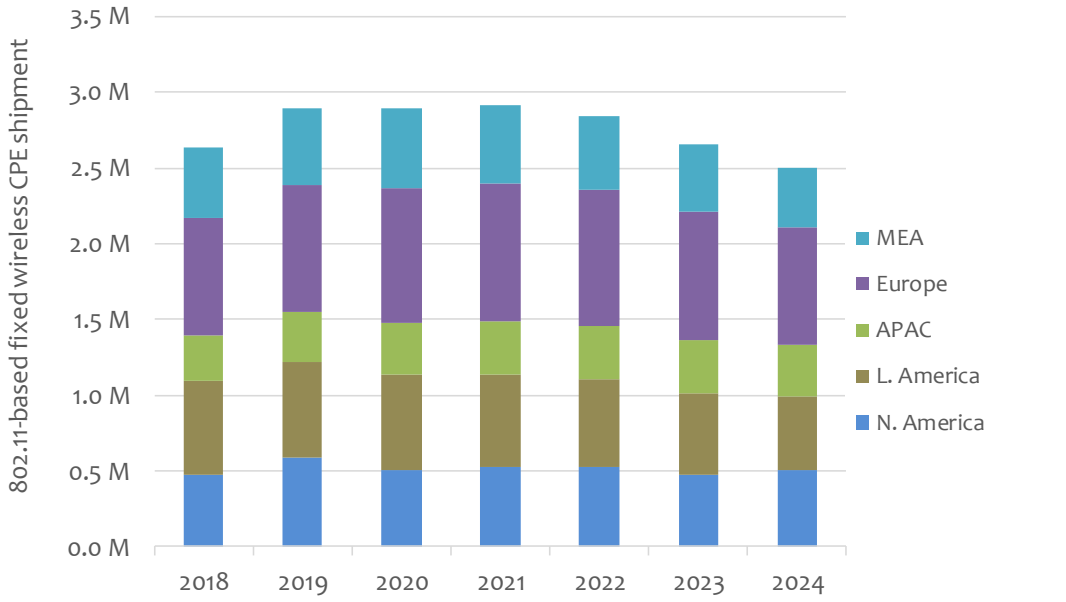
The core fixed wireless access markets addressed by WISPs in mostly rural locations is largely flat. While the opportunity to address replacement opportunities as old gear needs to be replaced, much of the growth will be driven from government funding in North America, more specifically CAF II and Rural Digital Opportunity Fund in the USA, and new spectrum opportunities in the millimeter wave bands (i.e., the 24-40 GHz lightly licensed and 60 GHz unlicensed bands).



Source: Mobile Experts

Chart 15: 802.11-based fixed wireless access AP shipment by region, 2018-2024

While the 802.11-based fixed wireless base station AP shipment will be largely flat in most regions like much of AP shipments will be geared towards replacement opportunities rather than greenfield deployments, North America is expected to see growth in the latter years in our forecast period as government funding will provide new infrastructure deployments in the "underserved" markets in rural and suburban areas. In other regions, most of the shipment activities will be based on incremental greenfield deployments but will be mostly based on replacement opportunities.



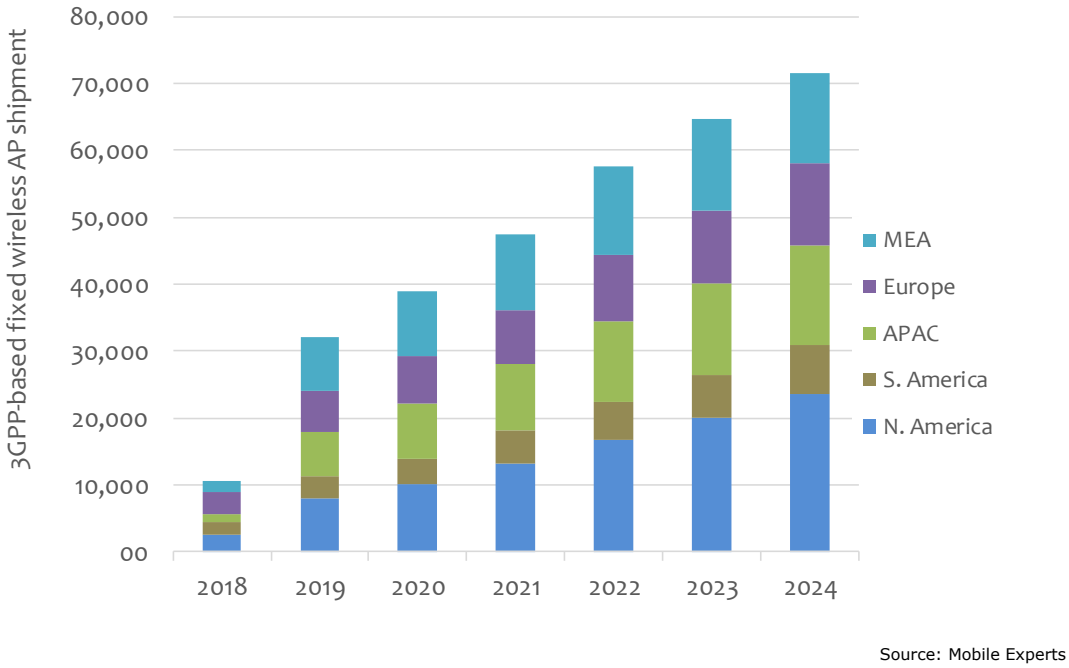
Source: Mobile Experts

Chart 16: 802.11-based fixed wireless access CPE shipment by region, 2018-2024

Meanwhile, some of the less-demanding broadband markets where expected broadband speeds are in the "tens of Mbps," like parts of South America and Africa, Mobile Experts forecasts operators to increasingly leverage LTE-based mobile networks to provide fixed broadband services to maximize network utilization. Hence, traditional 802.11-based proprietary solutions that have serviced this market is expected to decline over time.

3GPP-based FWA Equipment Outlook

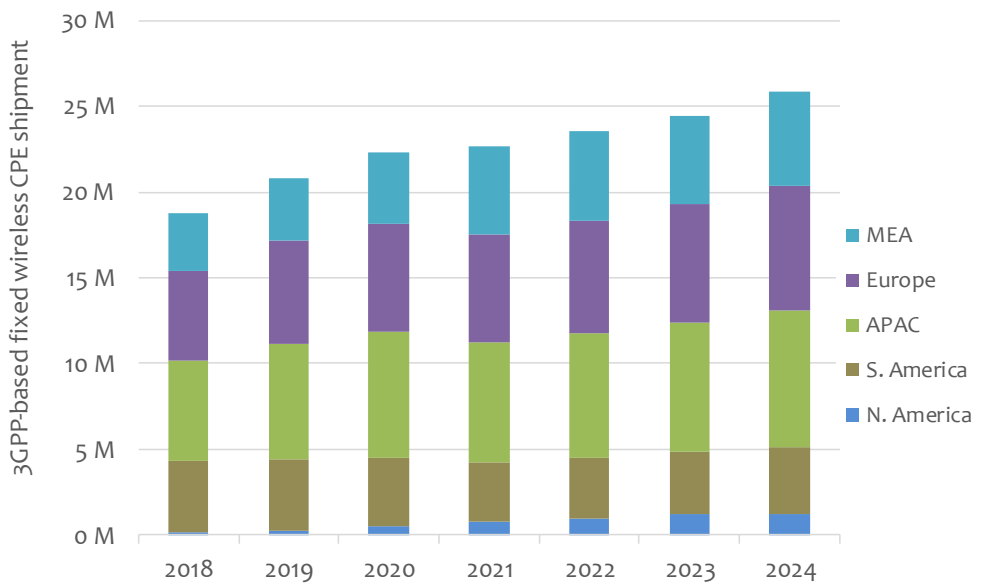
With lower cost LTE infrastructure gears coming to market from small cell vendors such as Parallel Wireless, Airspan, etc. and traditional fixed wireless vendors such as Cambium introducing LTE gears, we expect a good growth of both dedicated LTE base station AP shipments as well as steady growth in LTE and 5G CPE shipments. Starting from a small base, the combined LTE and 5G base station AP shipment are expected to grow at above 30% CAGR rising to over 70k units in 2024. Meanwhile, the combined LTE and 5G CPE unit shipments are projected to rise to just under 25M units in 2024 – a healthy 5% CAGR growth.



Source: Mobile Experts

Chart 17: 3GPP-based fixed wireless access AP shipment by region, 2018-2024

The overall uptrend of 3GPP-based fixed wireless access base stations is expected to be largely driven by the CBRS adoption in the USA and mobile operators' use of LTE mobile infrastructure to deliver fixed broadband service elsewhere especially in APAC, South America, and Europe. Moreover, 5G fixed deployment in select markets is expected to aid in the 3GPP-based AP shipment, but this portion is expected to be very modest.



Source: Mobile Experts

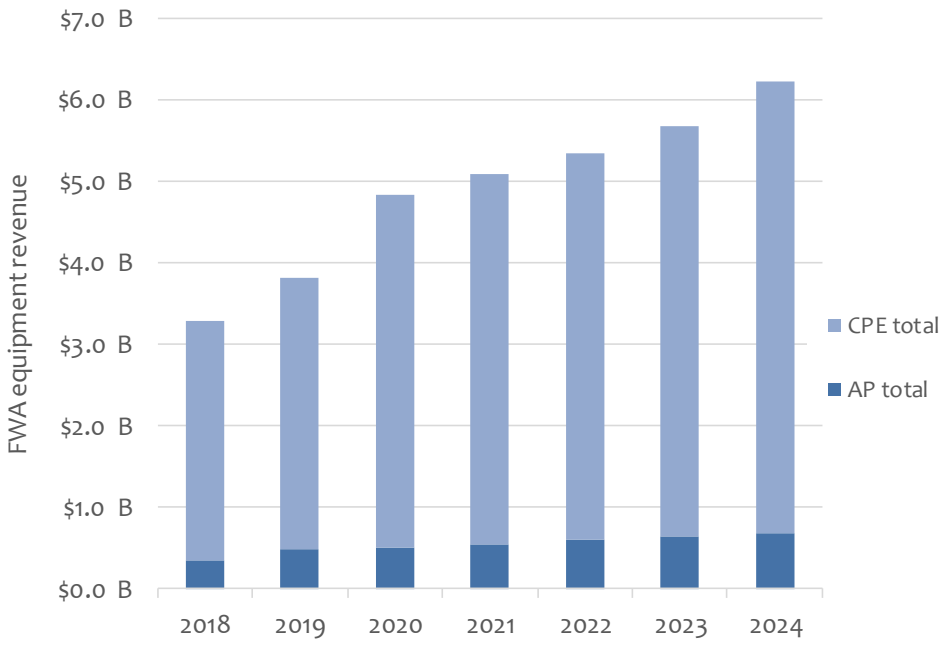
Chart 18: 3GPP-based fixed wireless access CPE shipment by region, 2018-2024

The annual LTE CPE unit shipment level is already at about 19M today. The trend of mobile operators shifting some of their mobile network infrastructure and spectrum towards fixed broadband is driving the unit shipments of LTE fixed CPE's. This activity is pretty small among major mobile operators in North America, but some of their 5G fixed trials and limited commercial launches are driving unit growth. The bulk of LTE fixed CPE shipment growth in the USA is expected to come from larger WISPs and more importantly, Telcos adopting fixed wireless to extend their wireline footprint with the aid of government funding. The 5G fixed adoption in both developed markets in Europe, APAC and the developed regions in the Middle East are expected to provide a significant growth as the major operators look to devote some of the 5G network capacity towards a replacement of outdated copper-based DSL broadband service.

7. FIXED WIRELESS ACCESS EQUIPMENT REVENUE

The fixed wireless access equipment market is predominantly driven by customer premise equipment (CPE) shipments as shown below. For every base station access point (AP) installed, multiple CPE's are deployed to maximize the utilization of the shared AP and network capacity.

(It should be noted that our AP shipment count and revenue forecast does not include LTE and 5G base station AP shipments that are "shared" across both mobile and fixed applications. We primarily count LTE and 5G base stations dedicated for fixed wireless use. While we expect some early 5G deployments to target fixed wireless application, in the beginning, many of those 5G base station deployments to be leveraged for mobile as well. Hence, our "dedicated" LTE and 5G base station AP revenue contribution as reflected in this report will be substantially less than actual Tier-1 operators' 5G infrastructure spend.)



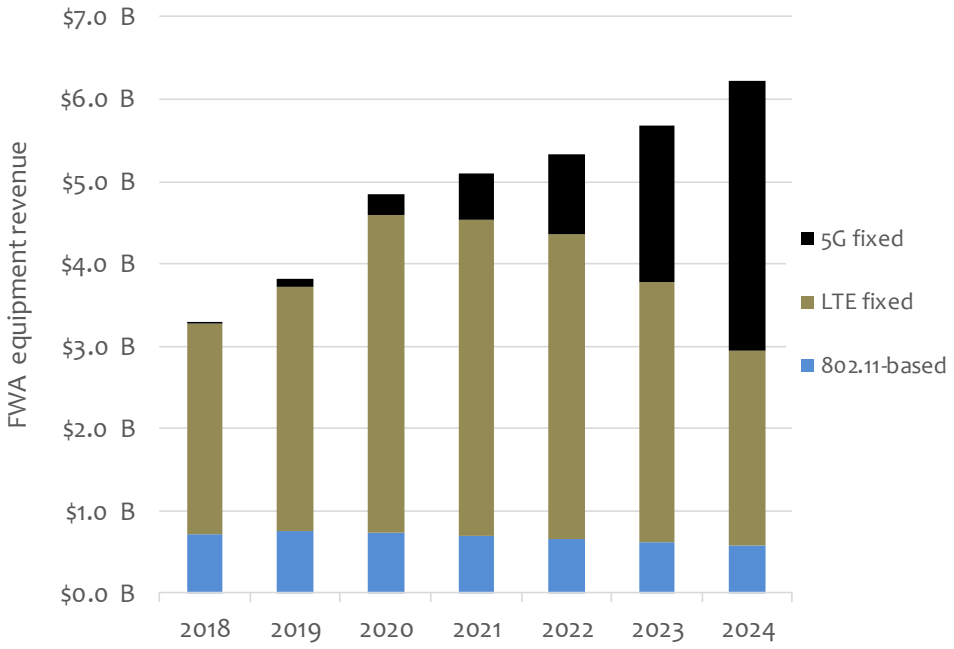
Source: Mobile Experts

Chart 19: FWA equipment revenue forecast, AP vs. CPE, 2018-2024

The larger CPE segment of the fixed wireless access equipment market is projected to grow at 11% CAGR, to over $6.2B in 2024, as higher-priced 5G fixed CPE shipments dominate in the latter years during the forecast period. Meanwhile, the base station AP segment of the market is expected to grow at over 10% during the same period, rising to just under $700M in 2024 especially as smaller operators and a smaller

number of mobile operators deploy dedicated LTE and 5G infrastructure for the fixed wireless purpose.

The overall fixed wireless *access* equipment market is forecasted to grow at 11% CAGR, rising from about $3.5B today to over $6.2B in 2024. As shown below, the "802.11-based" fixed wireless access equipment market generally targeting smaller operators will remain largely flat (with a slight decline during the forecast period) at around $600-700M annual revenue. (*Side note*: While we do not specifically track the broader *Wireless Broadband Equipment* market including the point-to-point equipment used for wireless backhaul to transport traffic to/from base station AP's to core network, and eventually to Internet Exchange points for Internet access, Mobile Experts estimates that this broader "outdoor Wi-Fi fixed wireless" market including much of the wireless equipment used for backhaul transport is slightly over 2x the size of the fixed wireless access market. Hence, we estimate that the broader *Wireless Broadband Equipment* market, including access and backhaul, is roughly $1.4 - 1.5B today.)



Source: Mobile Experts

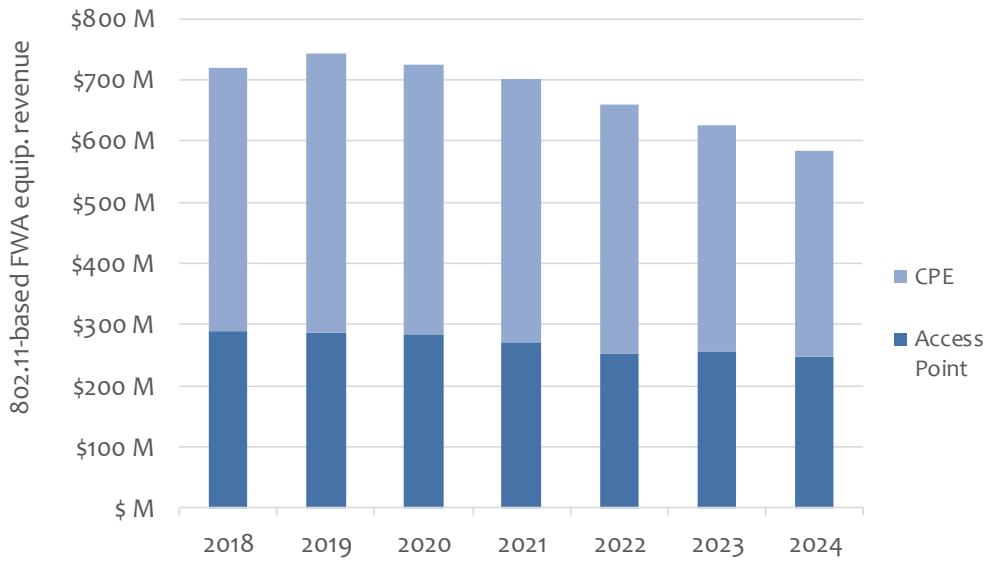
Chart 20: FWA equipment revenue forecast by technology, 2018-2024

The broader "3GPP-based" fixed wireless segment, including LTE and 5G, will grow at 8% CAGR during the forecast period – making up the majority share of the fixed wireless access equipment market. The "LTE fixed" segment will remain largely flat – rising to over $3.8B in 2020 then falling to $2.3B in 2024 as the "5G fixed" segment takes the majority share. The 5G fixed wireless market will rise quickly to over $3B in

2024 as large Tier-1 operators increasingly leverage their 5G networks to offer fixed wireless broadband service in addition to mobile. The growth in the fixed wireless access equipment market will come from 5G fixed as larger mobile/telco operators increasingly leverage a share of the increased mobile broadband capacity for in-home broadband service.

802.11-based Fixed Wireless Access Equipment Forecast

Much of the rural fixed wireless market has been served through "802.11-based" systems by smaller wireless ISPs (WISPs) over the years. While the market has been steadily growing, the majority of "rural" markets where economics have been favorable (i.e., enough subscriber demand to justify AP infrastructure deployment) has been addressed, and the bulk of equipment sales now come from replacements rather than "greenfield" deployments. As the new spectrum opportunities, such as 2.5 GHz and CBRS in the USA, come available, we expect larger operators with government funding will mostly look to LTE gear with a larger base of suppliers in the 3GPP ecosystem.



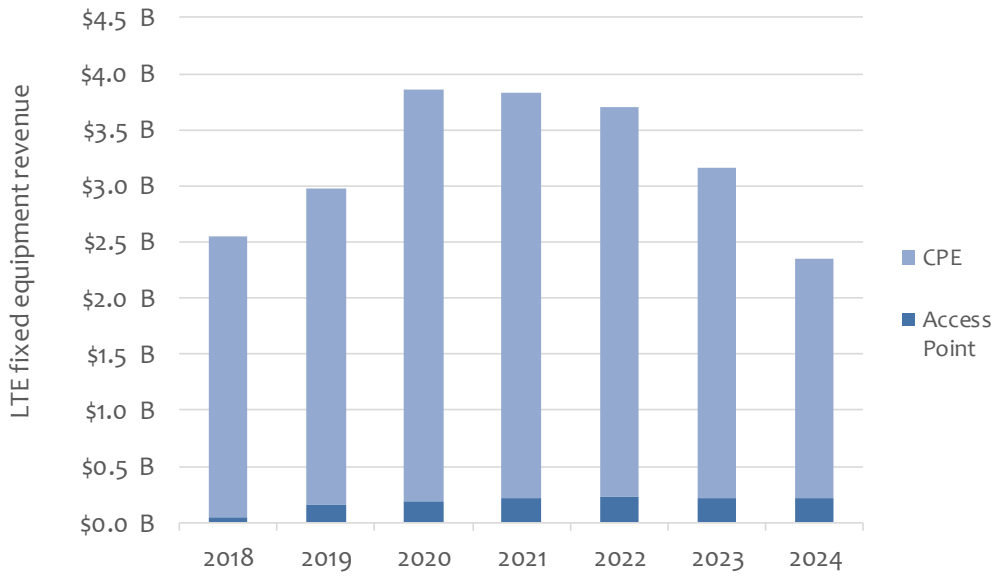
Source: Mobile Experts

Chart 21: 802.11-based fixed wireless access equipment revenue forecast, 2018-2024

The 802.11-based fixed wireless access equipment market will decline slightly during our forecast period from the height of about $700M this year to under $600M in 2024. The CPE segment will decline slightly faster than the base station AP segment as some larger WISPs, and regional Telcos will opt for LTE-based gear in new spectrum deployments such as CBRS.

LTE Fixed Wireless Access Equipment Forecast

LTE represents the largest technology segment of the fixed wireless access equipment market. In many developing markets with very little fixed broadband penetration, some incumbent mobile/telco operators are leveraging the mobile broadband network capacity for fixed broadband service through customer premise equipment at subscriber homes and business locations. Some WISPs are deploying dedicated LTE infrastructure for fixed wireless access, e.g., LTE gear running in the 5 GHz unlicensed and 3.5 GHz CBRS band. While not significantly meaningful to the overall equipment market (since CPE dominates), we expect this dedicated LTE base station AP market to continuously grow as the new spectrum opportunities in the 2.5 GHz, CBRS, and possibly in the 3.7-4.2 GHz mid-band come available.



Source: Mobile Experts

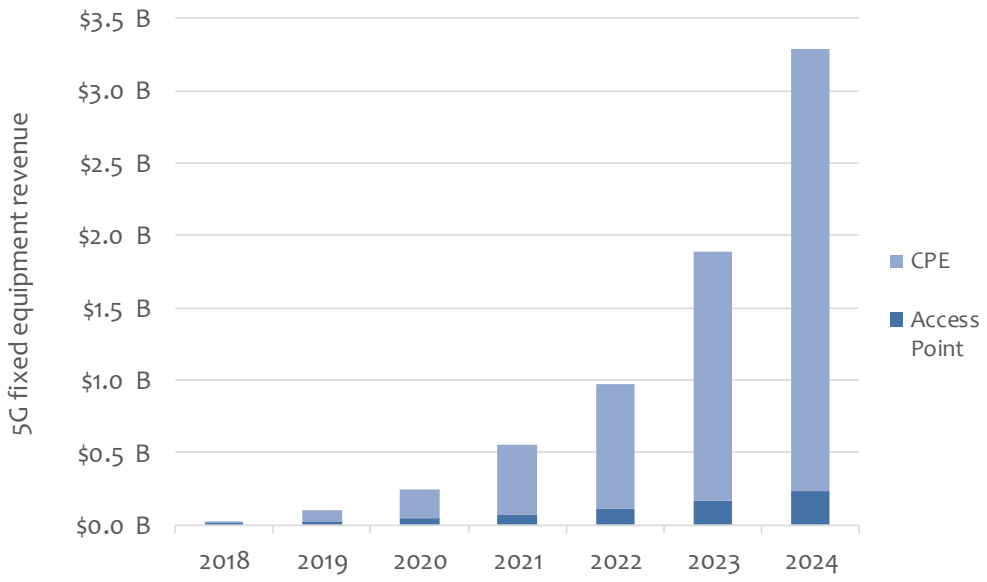
Chart 22: LTE fixed wireless access equipment revenue forecast, 2018-2024

The LTE fixed wireless access equipment market will increase near term, rising to just under $4B in 2020, and then decline as the 5G fixed take share away as the 5G fixed ecosystem quickly matures starting around 2022. Despite the growth in the dedicated LTE-fixed base station AP market during the forecast period, the overall market will decline at 1% CAGR as the dominant CPE market give way for the 5G fixed CPEs.

5G Fixed Wireless Access Equipment Forecast

The 5G fixed wireless access market is gaining momentum worldwide. As mobile/telco operators make the transition to 5G, one of the near-term use cases

with a proven business model is turning out to be the fixed wireless access market. Today, there are over 20 commercial 5G networks including Telenor, Vodafone, Elisa, Swisscom, etc. in Europe, Verizon, and AT&T in the USA, KT, SKT, and LG U+ in Korea, and many others. Despite the early lead in 5G fixed wireless deployments, we expect the 5G fixed deployment in the USA to be somewhat muted in the future as the operators will predominately dedicate their 5G network deployments for the mobile use case. However, we believe the 5G fixed market will flourish in markets where fixed broadband alternatives are scarce. For example, Elisa in Finland, Telenor Norway, and Telstra in Australia are some examples of operators looking to leverage 5G fixed broadband service to offer high-throughput in-home broadband services.



Source: Mobile Experts

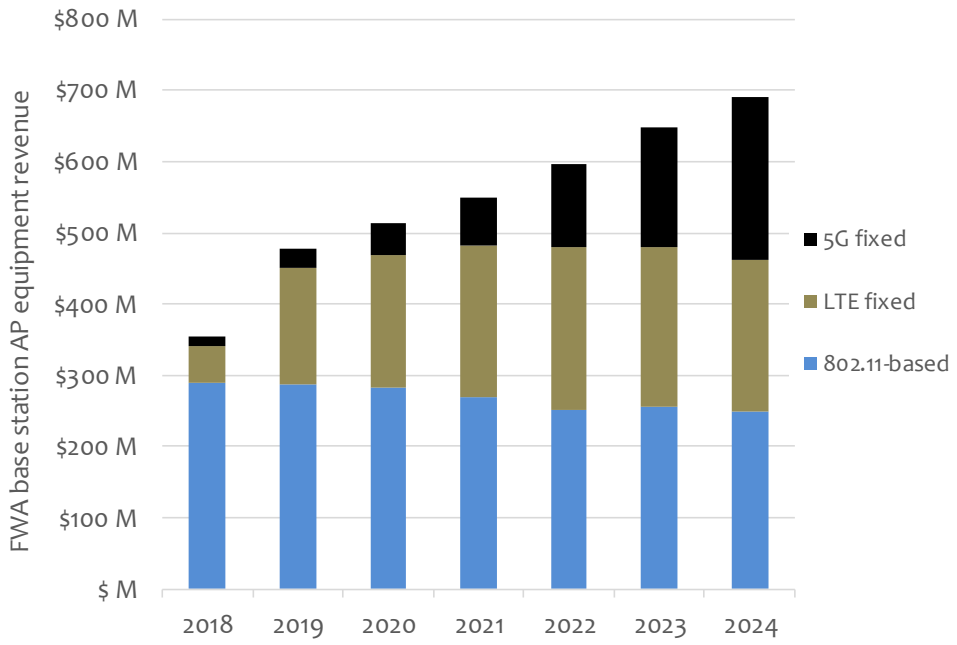
Chart 23: 5G fixed wireless access equipment revenue forecast, 2018-2024

The 5G fixed wireless access market will quickly grow to over $3B in 2024 with the CPE segment making up the majority of that equipment market. Mobile Experts believes that most mobile operators will choose to share their 5G network infrastructure for both fixed and mobile broadband offerings; hence, our "dedicated" base station AP contribution will be minimal.

Fixed Wireless Base Station AP Revenue

Since this report only tracks "dedicated" base station AP's used in fixed wireless access, the base station AP's make up a smaller portion of the overall fixed wireless access market. While the 802.11-based fixed wireless access gears are generally used for the fixed wireless application, LTE and 5G base station AP's are generally shared across mobile and fixed applications. Excluding the mobile RAN base stations that

are shared, the "dedicated" fixed wireless base station AP market is expected to rise quickly from about $350M in 2018 to about $700M in 2024.



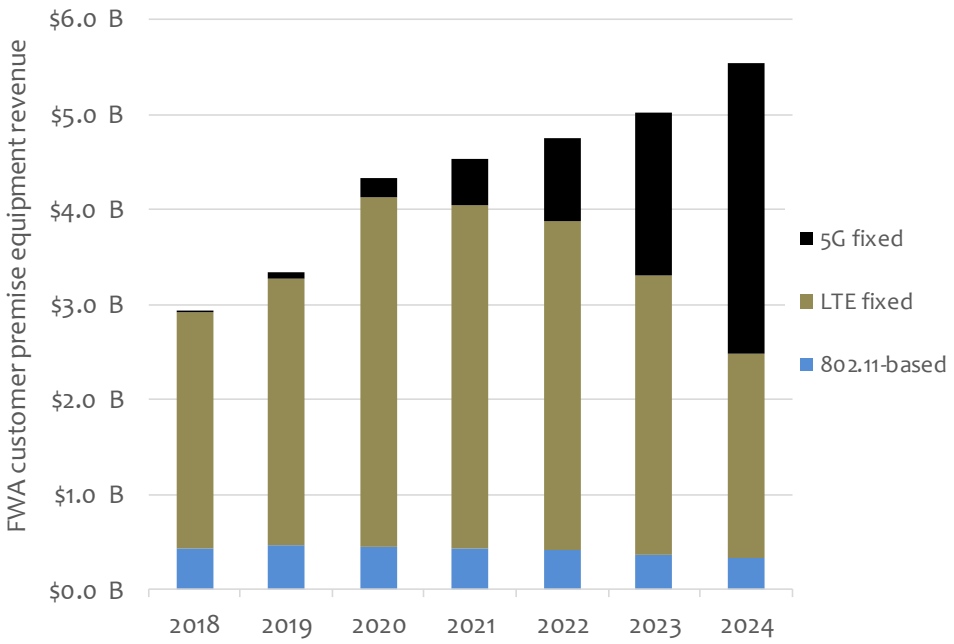
Source: Mobile Experts

Chart 24: Fixed wireless access base station AP revenue by technology, 2018-2024

While the 802.11-based fixed wireless base station AP market will decline slightly, the demand for this dedicated LTE base station AP's will grow as from Tier-2 and Tier-3 telcos and larger WISPs. Meanwhile, the 5G fixed AP revenue will be largely driven by Tier-1 operator launches, e.g., Verizon's 5G Home Broadband service.

Fixed Wireless Customer Premise Equipment (CPE) Revenue

As noted earlier, the fixed wireless access equipment market is dominated by CPE shipments. Within this segment, the equipment revenue from LTE CPEs already constitutes over 80% of the overall fixed CPE share today. The overall fixed wireless CPE market is forecasted to grow at 11% CAGR during the forecast period from about $3B in CPE sales in 2018 to $5.5B in 2024. The 802.11-based CPE sales will decline slightly from about $400M in 2018 to about $340M in 2024. This decline will be offset by the growth in the combined LTE and 5G CPE sales, which make up about 85-90% of the total fixed CPE sales during the forecast period.



Source: Mobile Experts

Chart 25: Fixed wireless access CPE revenue by technology, 2018-2024

8. COMPANY PROFILES

Airspan (acquired Mimosa Networks)

Based in the Silicon Valley, Mimosa sells mostly unlicensed PtP and PtMP radios for backhaul and access across multiple unlicensed and lightly licensed spectrum bands. The company has been promoting "Micro Pop" architecture to essentially densify fixed wireless networks into denser markets. With the Mimosa acquisition, Airspan continues to expand its product portfolio ranging from indoor and outdoor small cells and fixed wireless infrastructure and target markets from large mobile operators to smaller operators through distribution channels.

AT&T

AT&T is a major integrated mobile/telco operator with a multitude of network assets from nationwide wireless, fiber, copper, and satellite assets. The company is using its WCS spectrum dedicated for its fixed wireless broadband service mostly in rural areas to fulfill its CAF commitment. The company plans to cover 1 million residential and business locations by 2020. Its fixed wireless network dedicated to meet its FCC commitment now spans about 700,000 residential and business locations. The company has announced its plan to leverage the CBRS band for fixed wireless access using massive MIMO radios.

BaiCells

Founded in 2014, Baicells is a privately-held company based in Beijing, China. The company's product solutions range from indoor and outdoor small cells, CPEs, and antennas. With a new sales office in the Richardson, Texas, the company is targeting the WISP market with its outdoor LTE small cells, including those that operate in the 3.5 GHz CBRS band. The company offers a pathway for rural operators to transition fixed wireless LTE gears from Part 90 to Part 96 operation via software update.

Broadcom

As a major Wi-Fi chipset vendor, the company's chipset solution can be a foundation for 802.11-based fixed wireless infrastructure equipment. While the bulk of its Wi-Fi chipset sales derive from those embedded in smartphone units, the availability of its chipset solution for 802.11ax standards may become a major catalyst to broaden the ecosystem of 802.11-based fixed wireless CPEs.

Cambium Networks

Cambium was formed in late 2011 after the original Motorola Canopy business was sold to private equity. The company has a few R&D centers around the globe with its headquarter based in Rolling Meadows, IL. The company is believed to have about 500 employees with about $240M in annual sales. Its PMP 450 platform has been widely deployed around the world, and the company provides both point-to-point (PtP) and point-to-multipoint (PtMP) radio gears across a wide swath of spectrum bands. The company's product is considered "carrier" class among the WISP operators, and its product pricing reflects this as compared to some of its lower-cost peers. The company is working on LTE fixed wireless gear for introduction and is a member of Terragraph project to introduce 60 GHz point-to-multipoint product.

Cambridge Broadband Networks (CBNL)

CBNL is a UK-based company, which has been around since 2000, developing point-to-multipoint radios mostly in high-frequency bands. Its gears are widely deployed for access and backhaul for high-capacity enterprise access market. With high CPE cost associated with millimeter wave bands, it has found its niche in the enterprise fixed wireless space. The company had a limited fixed wireless deployment with Windstream in the 28 GHz band. It is an innovator in the PtMP millimeter wave radio. The company works with major service providers for niche fixed wireless deployments targeting enterprises in developing regions where wireline broadband is limited.

Casa Systems (NetComm Wireless)

Casa Systems has been building its wireless solution portfolio over the years, and its recent acquisition of Netcomm Wireless, a Sydney, Australia based company, bolsters its position in the fixed wireless space. In addition to its core business in cable infrastructure products, its wireless solution now spans from the converged core to small cells and now fixed wireless CPEs. Netcomm has a long history of supplying fixed wireless equipment and is a strategic supplier of fixed wireless gear in many Tier 1 accounts including AT&T and NBN in Australia.

CenturyLink

As one of the major Tier-2 Telcos in the USA, CenturyLink has a wide range of telecom assets including huge fiber footprint through its recent acquisitions of Level 3 and other enterprise businesses. As one of the "price cap" carriers for the CAF funding to deploy broadband access in underserved areas, CenturyLink is exploring fixed wireless access systems to deploy in the primarily rural markets in the CAF designated areas.

Comba Telecom

Comba holds a strong position in wireless solutions in China, as well as a few South Asian and Latin American markets. The company supplies a wide range of wireless infrastructure solutions, including repeaters, DAS, indoor and outdoor small cells, and customer premise equipment (CPE). In the fixed wireless space, the company primarily work on CPEs and has provided CPE under OEM agreements with large RAN vendors.

Consolidated Communications Holdings (CNSL)

CNSL is a leading broadband and business communications provider serving consumers, businesses of all sizes and wireless companies and carriers, across a 24-state service area, covering mostly Midwest, Northeast, Southeast, Texas, California, and Washington. The company serves over 1.5 million connections. Leveraging its advanced fiber-optic network spanning more than 36,000 fiber route miles, Consolidated Communications offers a wide range of communications solutions, including data, voice, video, managed services, cloud computing, and wireless backhaul.

C Spire

Also known as Cellular South, C Spire is a regional telecom operator based in Ridgeland, Mississippi, and is the sixth-largest wireless provider in the USA with an estimated 1 million mobile subscribers. The company has launched its "25 Mbps" fixed wireless service in eight markets, initially targeting 70,000 residential and business customers in Mississippi. The company announced that it would cover 200,000 customers with fixed wireless service and another 50,000 with FTTH. The company has formed Rural Broadband Consortium with Nokia, Mimosa, Siklu, and Microsoft to advance the fixed wireless access for rural markets.

Ericsson

As a major tier 1 telecom infrastructure vendor, Ericsson has also been participating in the fixed wireless market. Along with Samsung, Ericsson has been chosen as a select vendor in Verizon's 5G fixed deployment. Ericsson works with other third-party vendors like Netcomm Wireless and Comba to supply fixed wireless base station and CPE gears. Ericsson has partnered with Turkcell to launch 4G LTE fixed wireless service leveraging the operator's extensive spectrum holding to offer fixed wireless service tiers using Cat-6 and Cat-11 CPEs.

Frontier Communication

Frontier Communication is a tier 2 telco with numerous wireline connections, many of which it has acquired from Verizon. For example, it has acquired Verizon's FiOS footprint in Texas, Florida, and California in recent years. The company has confirmed that it is testing fixed wireless to address broadband connectivity to underserved areas. Frontier, like another tier 2 operators, who have received CAF funds to address broadband availability, are actively evaluating fixed wireless solutions.

Huawei

Huawei is a major global RAN vendor. With its incumbent position in the huge China mobile infrastructure market, the company has been actively growing its fixed wireless business primarily through leveraging the installed base of its LTE base stations and providing LTE CPEs to its mobile operator customers to expand into fixed wireless broadband access market. Under the "WTTx" (wireless to the X) product/business line name, the company is seeing good growth in APAC and other markets. The company has announced its 5G CPE product and is actively working several large mobile operators to launch 5G fixed broadband solutions.

IgniteNet

IgniteNet is a subsidiary of Accton, very large Taiwan-based ODM, and has been working on 60 GHz point-to-point and point-to-multipoint fixed wireless infrastructure for years. The company has introduced tri-band (2.4, 5, 60 GHz) radio that can provide a very high-throughput capacity at short range and provide fallback connectivity on 2.4 or 5 GHz when the 60 GHz link fails. The company has several commercial launches in smaller cities in Colorado and other countries.

Infinet Wireless

Infinet Wireless is an Russia-based wireless infrastructure company providing fixed wireless and private LTE markets with a proprietary technology. At MWC 2019, the company announced that it will be introducing 28 GHz point-to-multipoint product that can provide "100's Mbps at 5-6km range using tens of MHz of bandwidth." The company also has E-band point-to-point product that can provide several hundred Mbps links over 2-4 km reach. Like other proprietary vendors, it continues to see steady growth targeting private and regional communication service provider markets.

Intel

While the company has introduced 60 GHz WiGig chipset solution many years back, its solution is not known to be used in fixed wireless application. The company demonstrated outdoor repeater application leveraging its 60 GHz solution. Whether that particular solution may be extended to point-to-multipoint fixed wireless access application is not known.

Intracom Telecom

Based in Greece, Intracom Telecom has a long history in the market in delivering product solutions for wireless backhaul and broadband wireless access systems. It has 28 GHz PtMP product branded as "WiBAS-Connect" that is targeted for the fixed wireless access market. Also, it offers 60 GHz V-band and E-band PtP products for backhaul.

Linkem

Linkem is Italy's largest WISP that has over 1200 base station antennas, serving over 2000 municipalities in Italy. Its wireless network covers 40% of Italy's land mass. It has been transitioning its original WiMax network to LTE. It has LTE coverage in the 3.5 GHz band.

MediaTek

MediaTek is a major "merchant chipset" supplier to the mobile industry. As one of the main chipset competitors to Qualcomm in the end device ecosystem, its chipset announcements have generally acted as a catalyst to competitive, and generally lower, end devices such as smartphones and CPEs in the marketplace. The company has announced that its 5G modem chipset called Helio M70 will be sampling in the third quarter of 2019 and will be mass-producing its 5G chipset in early 2020. Mobile Experts believes that the company will be another major 5G NR chipset supplier to the 5G fixed wireless CPEs.

Microsoft

The Microsoft launched the Airband Initiative in 2017 to focus on using unused portions of broadcast channels also known as TV white spaces to deliver wireless connectivity in rural areas. The Airband project has a stated goal of extending high-speed internet access to 3 million people in rural America by mid-2022. Recently, Microsoft has worked with Watch Communications, Agile Networks, and Network Business Systems to deploy broadband connectivity in Indiana, Illinois, and Ohio.

MikroTik

MikroTik is a Latvian company founded in 1996. It has a long history in the fixed wireless industry offering very low-cost radio and networking gear for WISPs. Its company profile is similar to Ubiquiti except that MikroTik still largely work with Wi-Fi chipset companies and create hardware and surrounding software solutions for WISPs. Ubiquiti, on the other hand, has ventured into creating its proprietary chipset solution for its radio products. MikroTik has a strategic relationship with Qualcomm in leveraging Qualcomm's Wi-Fi chipset solution as an underlying baseline for its access, backhaul, and CPE products.

Nokia

As one of the leading global RAN infrastructure vendors, Nokia has a wide array of radio products. For the fixed wireless access market, the company provides multiple fixed wireless CPEs including "Wireless PON" based on 60 GHz unlicensed band and LTE and 5G "FastMile" CPEs running on licensed bands. The company's 5G gateway/CPE product operating in the sub-6GHz spectrum, which was launched at MWC 2019, has completed several commercial trials with major operators in Europe, APAC, MEA, and N. America. The company's 60GHz point-to-multipoint product based on the Terragraph Project is targeted for fiber replacement market in denser urban environments. Organizationally, the company's fixed wireless product group is a part of its Fixed Networks business along with PON and Cable products and provides sales channel paths to both fixed and mobile operators.

ON Semiconductor (acquired Quantenna)

Quantenna is a "high-end" Wi-Fi chipset supplier known for supplying highly-capable Wi-Fi solutions in wireless set-top boxes and cable modem gateways. The company also supplies its Wi-Fi chipset to Mimosa under strategic agreement. ON Semiconductor recently acquired the company for its Wi-Fi and other connectivity chipset solutions.

Peraso

Persaso is an early pioneer in the WiGig 60 GHz technology space. The company is a fabless semiconductor company based in Toronto. The company provides its 60 GHz chipset products for client devices as well as 60 GHz point-to-multipoint wireless infrastructure. The company provides millimeter wave chipset solution to a number of fixed wireless access equipment vendors.

Qualcomm

Qualcomm Atheros is a leading chipset vendor in the Wi-Fi market. In addition to traditional Wi-Fi and LTE small cell chipsets solutions, the company also offers 60 GHz chipset solution which is widely being used by multiple 60 GHz point-to-multipoint vendors to extend this newly tapped millimeter wave band. Along with its parent, Qualcomm is a major technology supplier into both licensed and unlicensed bands. Qualcomm is a leading vendor of the LAA, LTE-U, and MulteFire technologies.

RADwin

Headquartered in Tel Aviv, Israel, Radwin provide a suite of PtP and PtMP radio products for WISP and Carriers. Under the product branding of "JET" series, the company offers 5 GHz and 3.5 GHz radio gears for the WISP market. In addition to the fixed wireless access market, the company is positioning its JET products for Smart City and IoT applications to broaden the market appeal.

Redzone Wireless

Redzone Wireless is one of the leading WISPs in the USA serving over 100 communities in Maine. The company uses LTE on 2.5 GHz band and "5 GHz" technology to cover 225,000 households and 40,000 businesses across the state.

Rise Broadband

Rise Broadband, headquartered in Englewood, Colorado, is the largest WISP in the USA with about 200,000 residential and business customers. It has acquired over 100 WISPs since launching the company as JAB Wireless in 2005. The company has a combination of LTE and 802.11-based proprietary base stations in service. The company's annual revenue exceeds $200M and has over 800 employees.

Samsung

Samsung Networks is one of the key radio vendors for Verizon's 5G fixed trials and commercial launch. It has a history of delivering macro and small cell solutions to Jio in India and is one of the top two smartphone suppliers in the world. Samsung has its millimeter wave modem and RFIC which are instrumental in its 5G small cell products as well as enterprise-class LTE small cells and Wi-Fi access points.

Siklu

Siklu has a long history of delivering wireless backhaul solutions to WISPs and carriers. Based in Israel, the company was founded in 2008 and has recently gone through a management change. It has 70/80 GHz point to point backhaul product as

well as 60 GHz PtMP product that is it shipping today. Its leading market is North America with some market activities in Australia, the UK, Germany, and Africa.

Starry

Based in Boston, Starry has developed proprietary 37 GHz PtMP fixed wireless system leveraging underlying WI-Fi chipset solution from Marvell. Its "200 Mbps for $50" broadband service is now active in Boston and has announced further rollout of its network to 16 additional markets over the next year. Unlike traditional WISPs, Starry is targeting denser sub/urban markets leveraging large chunks of spectrum in the millimeter wave bands and highly capable (and costly at today's small-scale) CPEs to extend the millimeter wave coverage.

Tarana Wireless

Founded in 2009, Tarana has a long history in the wireless backhaul and access providing interference mitigation technologies to provide high-throughput capacity in backhaul and access deployments. The company recently received a fresh round of funding ($88M) with some notable investors including DISH/Echostar and the OneWeb founder. The company is expected to introduce gigabit fixed wireless solution targeting suburban segment of the market.

Telrad

Telrad offers LTE gear for WISPs in the 2.5 and 3.5 GHz band. It has recently signed an agreement with Federated Wireless to extend the operation of its LTE gears in the CBRS band. The company touts software-defined radio capabilities from its Alvarion acquisition. The wider Telrad parent company based in Israel has other businesses related to telecom.

T-Mobile US

With the pending merger with Sprint, the New T-Mobile has a huge swath of 2.5 GHz mid band spectrum for its 5G network buildout. In combination with massive MIMO, the company's 5G network based on 2.5 GHz spectrum is expected to significantly boost its network capacity and may afford to the company to provide a significant 5G fixed broadband network footprint.

Ubiquiti

Ubiquiti has a long history of delivering very low-cost radio gears for the WISP market. Under the AirMax brand, the company offers PtMP fixed access products across many spectrum bands. The AirFiber brand is associated with its wireless backhaul products with long-range and capacity. The company has been touting its

next-generation "LTU" platform which supports OFDMA (like LTE and 802.11ax) and other features to boost sector capacity and subscriber throughput speed. In the meantime, the company has created a successful enterprise Wi-Fi access point product line, which is growing faster than its original root in the fixed wireless industry.

Windstream

Like its tier 2 telco peers, Windstream is believed to be exploring a fixed wireless solution to meet its CAF commitment. Windstream already offers fixed wireless to its enterprise customers. It has launched 28GHz PtMP network in a handful of cities, but the network's future is uncertain as a result of Verizon acquisition of Straightpath whose spectrum was used in that network.

Verizon

As one of the leading operators in the world, Verizon has been at the forefront of 5G technology development. In addition to small cell deployments that are on-going, Verizon has actively trialed millimeter wave fixed wireless service in 11 markets, including Ann Arbor, Atlanta, Bernardsville, NJ, Brockton, MA, Dallas, Houston, Denver, Miami, Seattle, Washington, DC, and has announced commercial fixed wireless service launch in 3 to 5 cities, including Sacramento, in the second half of 2018 with a broader rollout planned in 2019. Verizon has acquired significant 28 and 39 GHz spectrum through XO and Straightpath acquisitions.

Vivint

Based in Utah, Vivint is a major "smart home" service provider, including home monitoring, video security, etc. The company's annual sales reach $700-800M. The company built out a fixed wireless network in Salt Lake City and a couple of cities in Texas. It is currently exploring new technology and spectrum options to extend its fixed wireless business but has been quiet for several months.

ZTE

As one of the major supplier of wireless infrastructure, ZTE provides RAN gear to domestic telecom operators in China as well as select customer base throughout the world. The company offers LTE gear for use in unlicensed bands for WISP market.

ZyXel

Based in Taiwan, ZyXel provides a wide array of wireless infrastructure products including small cells, repeaters, and LTE CPEs.

9. ACRONYMS

2G:	Second Generation Cellular
3G:	Third Generation Cellular
3GPP:	Third Generation Partnership Project
4G:	Fourth Generation Cellular
5G:	Fifth Generation Cellular
802.11:	IEEE standard for local area networking (extended to fixed wireless)
802.11ad:	An IEEE standard for 60 GHz short-range communications.
802.11ax:	A future IEEE standard for very high throughput in Wi-Fi.
802.11ay:	The next-generation 802.11ad that operates in 60 GHz band.
ADSL:	Asymmetric Digital Subscriber Line (slower DSL technology)
AP:	Access Point (Base Station)
BAS:	Broadcast Auxiliary Service (internal RF system used by a TV/radio station for backhaul channels from field to station)
BBU:	Baseband Unit
BRS:	Broadband Radio Service (FCC designation in the 2.5 GHz band)
CAF:	Connect America Fund
CARS:	Cable Television Relay Service (internal microwave systems used by cable and other pay TV operators)
CBRS:	Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US
CLEC:	Competitive Local Exchange Carrier
CPE:	Customer Premise Equipment (e.g., cable modem, broadband gateway)
CRAN:	Centralized RAN
dBm:	Decibels of power relative to 1mW
DFS:	Dynamic Frequency Selection
DSL:	Digital Subscriber Line (copper-based broadband technology)
EBS:	Educational Broadband Service (FCC designation of the 2.5 GHz band)

FCC:	Federal Communications Commission (US telecom regulator)
FPGA:	Field Programmable Gate Array
FTTH:	Fiber-to-the-Home
FWA:	Fixed Wireless Access
GAA:	General Authorized Access (in context of CBRS)
GHz:	Gigahertz
HD:	High Definition
IEEE:	Institute of Electrical and Electronics Engineers
IP:	Internet Protocol (or Intellectual Property)
IPv6:	Internet Protocol version 6
ITU:	International Telecommunications Union
LAA:	License Assisted Access
LTE:	Long Term Evolution
MAC:	Media Access Control (layer 2 in OSI model)
MDU:	Multi Dwelling Unit
MHz:	Megahertz
MIMO:	Multiple input, multiple output spatial multiplexing
MNO:	Mobile Network Operator
MSO:	Multi-Service (or System) Operator (reference to a cable operator)
MU-MIMO:	Multi-User MIMO
mmW:	millimeter wave
nLOS:	near Line of SIght
NLOS:	Non Line of Sight
NR:	New Radio (in context of 5G)
OTT:	Over the Top (Competitive Carrier)
PAL:	Priority Access License (in context of CBRS)
PtMP:	Point to Multi-Point (one to many radio link)
PtP:	Point to Point (one to one radio link)
RAN:	Radio Access Network

RF:	Radio Frequency
ROI:	Return on Investment
RRH:	Remote Radio Head
SAS:	Spectrum Access System (spectrum sharing database used in CBRS)
TDD:	Time Division Duplexing
TD-LTE:	Time Domain based Long Term Evolution
TDMA:	Time Divison Multiple Access
U-NII:	Unlicensed National Information Infrastructure
USF:	Universal Service Fund
WCS:	Wireless Communications Service (2305-2320 and 2345-2360 spectrum)
Wi-Fi:	Wireless Fidelity (unlicensed wireless communications)
WiGig:	Wireless Gigabit (60 GHz unlicensed band)
WISP:	Wireless Internet Service Provider (independent FWA operator)

10. METHODOLOGY

To create estimates and forecasts for Fixed Wireless Access equipment shipments, Mobile Experts relied on direct input from more than 20 industry sources, including input from multiple wireless ISPs contributing to the overall analysis to give a detailed global view of the market. Mobile Experts built a "top-down" forecast based on direct input from operators, as well as overall trends in end-user demand for mobile services. Then, Mobile Experts built a "bottom-up" forecast through discussions with the supply chain, including vendor suppliers, top-tier OEMs, and component suppliers. Mobile Experts also used financial disclosures from publicly traded companies to assemble a quantitative view of the equipment market.

Mobile Experts has defined market segments in a new way to achieve more clarity than other analysts in this area.

In particular, Mobile Experts has clearly drawn a distinction in this report between 3GPP fixed wireless access and 3GPP mobile access. Fixed users are defined as those with a CPE in a set location, at a home or office. If a base station is "shared" between mobile users and fixed users, then it's not counted here.